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THE ENERGY BUDGET AT THE EARTH'S SURFACE

Part I

Production Research Report No. 71

Agricultural Research Service
U.S. DEPARTMENT OF AGRICULTURE
In cooperation with
NEW YORK STATE COLLEGE OF AGRICULTURE
For
Meteorology Department
U.S. ARMY ELECTRONIC PROVING GROUND

USAEPG SUMMARY

DA Task: 3A99–27–005–08 Micrometeorology (USAEPG)
Title: The Energy Budget at the Earth's Surface: Part I
Originator: Agricultural Research Service, U.S. Department of Agriculture, Ithaca, N.Y.

The objective of Task 3A99–27–005–08, "Micrometeorology (USAEPG)," is to conduct studies dealing with the physical processes involved in the exchange of energy between the atmosphere and the earth's surface. Through such basic research, knowledge of atmospheric processes will be increased and ultimately contribute to advancing the state-of-the-art in weather forecasting.

Research shall be conducted to study the soil, plant, and meteorological interactions involved in the partitioning of thermal energy at the earth's surface. Field experiments shall be conducted at which measurements of long and short wave radiant exchange and soil conduction shall be made. In addition, measurements to determine the vertical gradients of momentum, potential temperature, absolute humidity, and carbon dioxide shall be made and computations shall be carried out using various aerodynamic formulas to determine the "effective" surface shearing stress, the turbulent transfer of latent and sensible heat, and the consumption of energy by photochemical action (photosynthesis). The basic measurements (excluding soil heat conduction) shall be made above the "effective surface" in the surface boundary layer. Nevertheless, consideration will be given also to the turbulent transfer characteristics and source (or sink) distributions within the vegetative canopy. The partitioning of the energy transfer shall be correlated with soil, plant, and meteorological characteristics such as soil moisture, plant water conditions (for example, relative turgor), stage of vegetative growth, shearing stress, and aerodynamic roughness of the "effective" surface.

Laboratory experiments shall be conducted to study the physiological characteristics of plants as they pertain to photosynthesis and transpiration. Further laboratory experiments and evaluations shall be carried out to determine the aerodynamic roughness characteristics of natural and simulated surfaces (both rigid and nonrigid).

METEOROLOGY DEPARTMENT
USAEPG

This study was conducted under Interdepartmental Cross Service Order No. 3–59, dated 24 February 1959, which is authorized in letter OCSigO, SIGRD–8b–5, dated 13 August 1957, "Proposed Coordinated Signal Corps Meteorological Program."

THE ENERGY BUDGET AT THE EARTH'S SURFACE

Part I

Preliminary Studies at Ithaca, N.Y., 1959

Agricultural Research Service
U.S. DEPARTMENT OF AGRICULTURE
In Cooperation With
The Department of Agronomy
N.Y. STATE COLLEGE OF AGRICULTURE
Cornell University
for
Meteorology Department
U.S. ARMY ELECTRONIC PROVING GROUND
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Production Research Report No. 71

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CONTENTS

THE ENERGY BUDGET AT THE EARTH'S SURFACE: Part I

SUMMARY

Representative energy balance data over corn and alfalfa fields point up the importance that leaf cover (and thus "surface wetness") has in affecting the partition of net radiation. In a cornfield sensible heat exchange in the soil and the air was proportionately greater than in an alfalfa field where more energy was exchanged as latent heat. Energy balance studies in a wintertime snowfield under solar radiation intensities comparable to those in a summertime cornfield reveal how important albedo (solar radiation reflection) is to the energy balance.

In an investigation of the surface aerodynamic properties of a cornfield, it was found that the elastic properties of the surface cause the "roughness length" to increase with windspeed, and the "crop displacement" to decrease with windspeed. This suggests that with increasing windspeed the corn crop surface appears to increase in roughness length, and thus act as a greater momentum sink.

Theoretical estimates of the role played by photosynthesis in the energy balance reveal the possibility of much greater energy utilization in the photochemical fixation of carbon dioxide than was heretofore realized.

OBJECTIVES OF 1959 STUDIES

The objectives of this study are to characterize, understand, and ultimately control, to some degree, the plant, soil, and meteorological interactions involved in the partition of thermal energy at the earth's surface. Basically, the major objectives stem from the need for better understanding of the processes controlling the climate near the ground. Specifically, the objective of this research effort is to conduct studies and field experiments to evaluate the influence of the various boundary characteristics on the energy budget at the earth's surface. Special attention has been given to the characteristics of the surface cover as it influences the turbulent transfer and to the contribution of photochemical fixation of carbon dioxide to the energy balance.

Part I includes the experimental results of the preliminary phases of the study during the period July 1, 1959, to July 1, 1960. Delays in equipment delivery allowed only a modest field program during this period. Nevertheless, intermittent studies with equipment on hand permitted collection of representative heat budget data over a cornfield and an alfalfa field during the summertime growing period, and over a snowfield in winter. With sufficient experimental data as a guide, progress was made in the theoretical evaluation of the potential proportion of the heat budget devoted to the photochemical fixation of carbon dioxide during photosynthesis.

Specifying and predicting the dynamics of the atmospheric boundary layer, i.e., the layer of the atmosphere extending from the surface to approximately 3,000 feet, require a knowledge of energy transfers and transformations at the earth-air interface and within the boundary layer itself. The various modes of energy transfer at the earth's surface lie in a delicate balance.

A valuable tool used in studying the problem of energy transfer is an application of the law of the conservation of energy. Since energy can neither be created nor destroyed, an attempt is made to account for all of the radiant energy received at the surface of the earth. This energy heats the air, heats the soil, evaporates water from the soil and plant surfaces, and goes into plant material through photosynthesis. The partition of this energy can be expressed in the following equation:

$$R_n = H + E + S + P \tag{1}$$

Where

R_n = the net radiation received at the surface of the earth;

H = the heat convected and conducted into the air—sensible heat;

E = the heat used in evaporating water—latent heat;

S = the heat conducted into the soil;

P = the energy used in creating plant tissue—photosynthesis.

In practice, the net radiation and heat conduction into the soil can be measured without much difficulty. However, the evaluation of the turbulent transfers of sensible and latent heat present formidable problems in both measurement and

interpretation, since they both involve aerodynamic transfer processes.

Photosynthesis, the photochemical fixation of carbon dioxide in green plants, requires that carbon dioxide be brought to the leaf surfaces. This transfer of carbon dioxide is accomplished by aerodynamic processes also.

In evaluating the sensible heat, latent heat, and photosynthesis terms in the above equation, it is therefore necessary to gain insight into the aerodynamic exchange equations and the aerodynamic method of evaluating these exchanges. The first study contains a thorough discussion of pertinent theory, problems of field site consideration, and the roles of surface roughness and zero plane displacement in the application of the aerodynamic method of determining exchange in a fully developed, turbulent boundary layer.

Experimental determination of the terms in the energy balance equation 1 and a study of surface effects on the wind profile are reported in the second study. The effects of varying surface geometry and elasticity on the shape of the wind profile were brought into clearer focus through field experiments in which wind profiles were measured over a uniformly developed crop with cross-row and along-row wind fetches and, for a period of time, over a growing crop.

In the third section of this report photosynthesis is discussed from the theoretical standpoint and in the light of field experiments in which carbon dioxide exchange measurements were used. This discussion serves to illuminate the role played by photosynthesis in the partition of energy at the earth's surface.

THEORETICAL CONSIDERATIONS OF AERODYNAMIC EXCHANGE IN A TURBULENT BOUNDARY LAYER

By E. R. Lemon

THEORY

As an example of eddy flux determination, the aerodynamic method is applied here to the determination of carbon dioxide exchange (*12*).[1] It is based upon the careful measurement of the small windspeed gradients and carbon dioxide gradients existing above a crop surface in the fully developed turbulent boundary layer. The method depends upon three assumptions for the shallow turbulent boundary layer.

(1) The vertical gradient of windspeed expressed by

$$\frac{\partial u}{\partial z}=\frac{1}{k}\left(\frac{\gamma_0}{\rho}\right)^{1/2}\frac{1}{z} \qquad (2)$$

upon integration gives a well-known logarithmic law where the windspeed u_z at height z is represented by

$$u_z=\frac{1}{k}\left(\frac{\tau_0}{\rho}\right)^{1/2}\ln\left(\frac{z+z_0}{z_0}\right)\text{ where } z>z_{00} \qquad (3)$$

τ_0 is the shearing stress at the surface; ρ is the density of the air; z_0 is the "roughness length," which is the constant of integration characteristic of the given surface; and k is a universal constant having a value of 0.40 (Kármán's constant).

(2) The shearing stress, τ, is constant with height.

(3) The eddy diffusivity for carbon dioxide, Kc, is identical to that for momentum, Km, where $Km=\frac{\tau/\rho}{\partial u/\partial z}$.

If these assumptions are acceptable, then for the process of carbon dioxide transfer,

$$P=-Kc\,\frac{\partial C}{\partial z} \qquad (4)$$

where P is the rate of carbon dioxide exchange and C the carbon dioxide concentration. By substitution for Kc and integration between the heights z_1 and z_2, we have

$$P=\frac{k^2(u_2-u_1)(C_1-C_2)}{(\ln z_2/z_1)^2} \qquad (5)$$

[1] Italic numerals in parentheses refer to Literature Cited, p. 32.

If assumptions (1), (2), and (3) above are accepted, the rate of carbon dioxide exchange, P (g./cm.^{2}/sec.), can be calculated by using equation 5, where u_1 and u_2 and C_2 and C_1 are the measured wind velocities (cm./sec.) and carbon dioxide concentration (gm./cm.^{3}) at the two different heights, z_1, z_2 (cm.) above the crop. Similar equations (*7, 13, 14, 20, 22, 26*) have proved valid for water vapor and sensible heat exchange under near-isothermal conditions. Inoue's use of equation 5 for calculating carbon dioxide exchange has demonstrated reasonable rates (*8, 9, 10, 11*). No simultaneous independent check of carbon dioxide exchange rates has been made, however, because of the extremely difficult experimental problems (*18*). Recently, dry matter increase in sugar beets has been compared to calculated carbon dioxide exchange rates (*16*).

SITE REQUIREMENTS

Usually, upwind "fetch" over homogeneous level surfaces has been sufficiently great in aerodynamic studies to insure equilibrium gradients in the turbulent airstream within the first few meters of the land surface. The application of equation 5 to level cornfields of limited extent, such as in the hilly area of Ithaca, N.Y., presents special consideration of site selection, however.

Let us consider figure 1. The wind is blowing from left to right, and the length of the arrows of

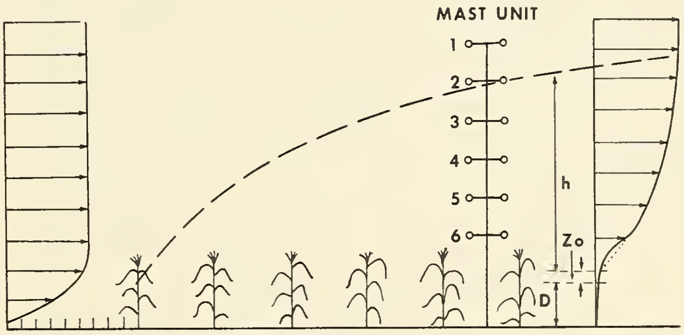

Figure 1.—Schematic diagram of growth of the boundary layer over a cornfield. Arrows indicate wind direction and relative windspeed in wind profiles.

the two wind profiles gives a relative idea of the windspeed over the two dissimilar surfaces (alfalfa upwind and corn downwind, for example). When the equilibrium wind for the alfalfa strikes the

corn, a new equilibrium boundary layer (below dashed line) grows as the "fetch" increases downwind. Above this boundary layer the windspeed profile and other components reflect the intermixing of other boundary layers developed upstream. Within the boundary layer, the equilibrium gradients of wind, temperature, water vapor, and carbon dioxide only reflect the homogeneous surface of the cornfield. In making measurements of these gradients in order to utilize equations like 5 for flux determinations, it is important to stay within the boundary layer of the particular surface being investigated. It has been shown that the height of the boundary layer, h, is approximately defined by:

$$h=0.75\ X^{0.8} \tag{6}$$

where X is the distance from the leading edge (*3*). Since the boundary layer is displaced upward as the crop grows, the reference plane from which h is measured necessarily moves up also. This distance, z_0+d, is called the "effective displacement," and is discussed in the next subsection.

Referring to figure 1 again, the measuring elements near the top of the mast (Nos. 1 and 2) are pictured above the boundary layer, and therefore they do not characterize the corn crop. Those elements in the boundary layer (Nos. 3 through 6) should reflect equilibrium gradients generated only by the corn crop. Errors in equation 5 due to thermal gradients can be minimized, however, by making measurements as low in the boundary layer as practical (*7*). Care must be taken, on the other hand, in selecting the lowest element height, since it should not be so low as to reflect small local patchiness, i.e., a nearby corn tassel. The height-interval of the measuring elements within the boundary layer is determined by the sensitivity and accuracy of the elements measuring small differentials between selected heights. In figure 1 it is obvious that gradient measurements must be made closer to the alfalfa crop than to the corn crop. Likewise, it is obvious that in small cornfields, restriction on boundary layer thickness requires difficult measurements of small gradients within a shallow boundary layer.

DETERMINATION OF THE "EFFECTIVE DISPLACEMENT"

Equations 3 and 5 imply that the windspeed and carbon dioxide concentration profiles are functions of log height, z, above a given reference plane. Where relatively smooth surfaces are involved, i.e., a clipped sward, this reference plane is taken to be the solid ground—atmosphere interface. As a crop like corn grows in height, however, the turbulent boundary layer is displaced upward, causing the reference plane from which z is measured to be displaced upwards above the ground surface. Since fully developed turbulent profiles occur in the boundary layer somewhat above the crop surface, an analysis of the isothermal wind profile in this region, either graphically or statistically, has to be employed to find where this reference plane is in relation to the ground surface.

This is dictated by assumption (1) above, where in equation 3 the windspeed observations take u vs. log z form. It becomes necessary, therefore, to introduce a zero point displacement, d, and rewrite equations 3 and 5 thusly (*17*):

$$u_{z_i+D}=\frac{1}{k}\left(\frac{\tau_0}{\rho}\right)^{1/2}\ln\left(\frac{z_i+D}{z_0}\right) \tag{7}$$

$$P=k^2\,\frac{(u_2-u_1)(C_1-C_2)}{(\ln z_2+D/z_1+D)^2} \tag{8}$$

where $D=d+z_0$ is the "effectiveness displacement" parameter, and z_i is the nominal height (i.e., z_1 and z_2) of the anemometers measured from the ground surface.

For water vapor transfer, equation 8 becomes:

$$E=k^2\,\frac{(u_2-u_1)(e_1-e_2)}{(\ln z_2+D/z_1+D)^2} \tag{8a}$$

where E is the evaporation rate in g./cm.^{2}/sec. when e is absolute humidity or vapor density in g./cm.^{3}.

For sensible heat transfer, equation 8 becomes:

$$H=\rho C_p k^2\,\frac{(u_2-u_1)(T_1-T_2)}{(\ln z_2+D/z_1+D)^2} \tag{8b}$$

where H is the sensible heat transfer in cal./cm.^{2}/sec.; ρ is the density of the air (0.00110 g./cm.^{3}); C_p is the specific heat of the air (0.24 cal./g.–deg.); and T is the air temperature (°C.).

Figure 2 presents a schematic interpretation of the surface parameters. Since the linear u vs. log z_i+D extrapolates to a positive value of z_i+D (the roughness length, z_0) where $u=0$, the true reference plane (where $z_i+d=0$) lies at a distance, d, above the ground surface.

In the graphical analysis, arbitrary values of D are tried where there are windspeed data for three or more levels, z_i, until the corrected assumed value of D gives a linear plot. Figure 2 presents a graphical analysis of one isothermal profile taken over corn that was 240 cm. high, with a wind fetch of 500 meters. Three different values of D were selected for illustrative purposes. A selected value, −150 cm. for D, evidently was too large, since the points on the graph give a concave downward effect. If one chooses a D value too small (−50 cm.), the points lie on a concave

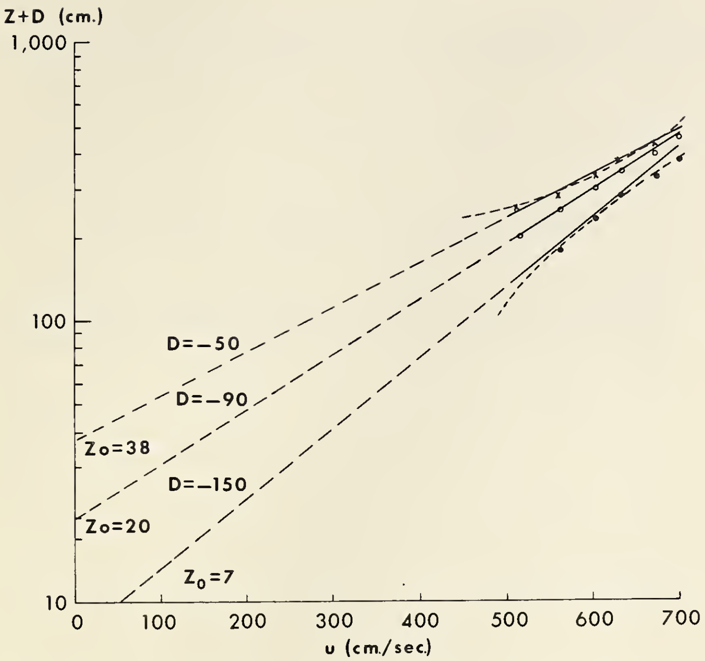

FIGURE 2.—Graphical analysis of wind profile (readings taken 1033 e.s.t., Sept. 19, 1957) for three assumed values of *D*.

upward curve. The correct *D* value apparently equals −90 cm., since all the points lie on a straight line. The correct roughness length, z_0, is 20 cm., and the correct crop displacement or zero plane displacement, *d*, is then −110 cm.

In a numerical trial and error least squares method, various values of *D* different from zero are tried until the sum of the squared deviations, E_i^2, has the least value.[2] Let us rewrite equation 7, thus:

$$u_1 = u^* \ln \frac{z+D}{z_0},\ i=1 \text{ to } n \tag{9}$$

where *n* is equal to or greater than 3 and $u^*=1/k \left(\frac{\tau_0}{\rho}\right)^{1/2}$, and is called the "friction velocity."

If the following equations are utilized:

$$E_i = Xi - u^* Yi \tag{10}$$

$$u^* = S_{XY}/S_{YY}. \tag{11}$$

The deviations *Ei* are obtained directly by defining:

$$Xi = u_i - \bar{u};\ \text{where } \bar{u} = \frac{\text{Sum } u_i}{n},$$

$$Yi = \ln z_i + D - \overline{\ln z_i + D};\ \text{where } \overline{\ln z_i + D} = \frac{\text{Sum} \ln z_i + D}{n},$$

$$S_{XY} = \text{Sum } (XiYi),$$

$$S_{YY} = \text{Sum } (YiYi).$$

The roughness parameter, z_0, can now be solved by

$$\ln z_0 = \overline{\ln z_i + D} = \bar{u}/u^*. \tag{12}$$

Surface stress or ground drag, τ_0, now is defined by

$$\tau_0 = k\rho u^{*2},\ \text{where } k=0.4. \tag{13}$$

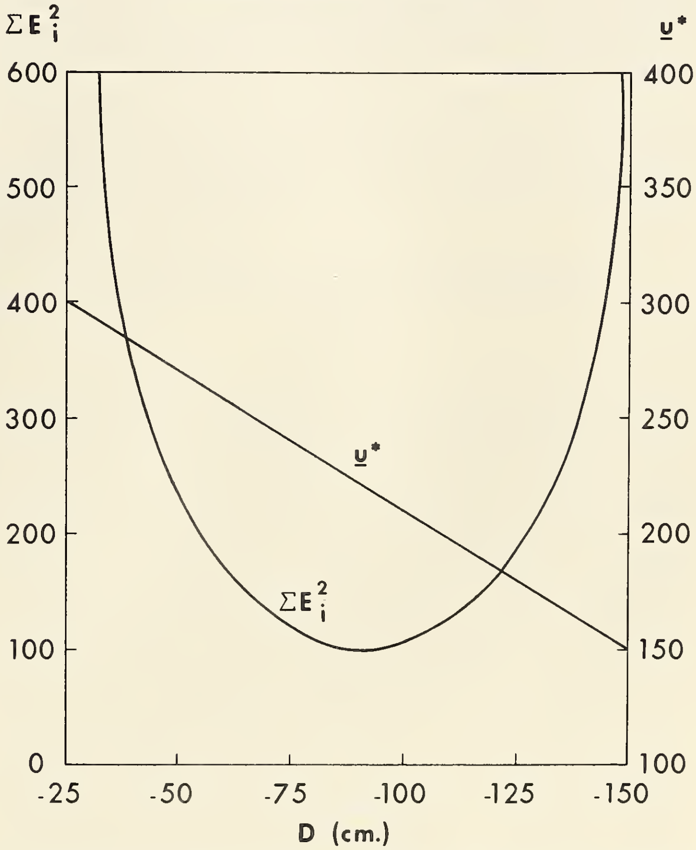

FIGURE 3.—Graph of statistical analysis of wind profile (readings taken 1033 e.s.t., Sept. 19, 1957) demonstrates the manner in which friction velocity, u^*, and the sum of the squared deviations depend upon the assumed values of *D*.

Figure 3 demonstrates the relationship between the effective displacement, *D*, the sum of the squared deviations, E_i^2, and the friction velocity, u^*, for the same profile analyzed graphically in figure 2. It should be pointed out that an overestimation of *D* will result in an exchange determination too low (the friction velocity is too low), whereas an underestimation of *D* will result in an exchange rate determination too high (the friction velocity is too high).

[2] The method used here was suggested by H. H. Lettau in a personal communication. (See also *14, pp. 334–335.*)

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Aerodynamic exchange studies in the past have usually dealt with low vegetation or relatively smooth surfaces. Under such conditions, the roughness elements appear to be fairly rigid so that d and z_0 values are constant for a given surface at all windspeeds normally encountered. On the other hand, taller crops appear to be very elastic, even at relatively low windspeeds. Rider (*20*) has reported functional changes in d values with changes in windspeed over a waving oat crop.

An additional point should be brought up regarding the wind profile within the crop itself. It has been pointed out above that an extrapolation of the wind profile taken in the fully turbulent layer somewhat above the corn gives the roughness length, z_0, where $u=0$. In reality, the wind profile diverges from the normal u vs. $\log z$ form within the crop, and immediately above. This is pictured in the schematic wind profiles in figure 1, where the dotted line represents the ideal fully turbulent profile. It is below the dotted line, within the crop, where little understood turbulence characteristics really play an important role in controlling gaseous exchange. Turbulence levels above the crop give insight as to relative turbulence in the crop. The region within the crop itself warrants serious study now, however.

EXPERIMENTAL DETERMINATION OF THE ENERGY BALANCE

By Edgar R. Lemon, Joseph H. Shinn, and J. H. Stoller

EXPERIMENTAL FIELD SITE

An experimental site was developed in a small valley called Ellis Hollow, 5 miles east of Ithaca, N.Y. The site (fig. 4) is located on the valley floor with a 3 percent slope toward a small stream draining the valley. Wooded hills border the north, south, and east sides of the valley. Despite the fact that the terrain is far from an ideal infinite homogenous surface, and therefore not suitable for certain types of micro-meteorological studies, it is representative of much of New York's agricultural land. It has proved to be acceptable for our purposes, provided particular precautions are taken in locating sampling sites.

Figure 5 gives the field plan of the experimental site. Two relatively smooth and level (3 percent southwest slope) adjacent fields were available on a well-drained stony soil (Chenango stony silt loam). The southwest field, which was planted to corn, has approximate dimensions of 1,100 by 450 feet, with the longer axis oriented northwest and southeast. The second field, which is in alfalfa sod, has the dimensions 1,100 by 700 feet, oriented in the same direction, and lies immediately northeast of the cornfield. The area is bordered by a few scattered trees on the northwest and southeast sides, with a solid woods to the southwest.

Fortuitously, the prevailing winds in the valley are from the northwest and southeast parallel to the longer axes of the two fields. Sufficient fetch in the center of the corn and alfalfa fields provides a turbulent boundary layer 3 to 4 meters deep. Micrometeorological sampling sites were located on an instrument line running southwest and northeast through the center of both fields. Much of the heat budget data, however, for the earlier part of the 1959 growing season were obtained from a satellite station 200 feet northwest of the central cornfield sampling site. Fetch was sufficient at the satellite station to give at least a 2-meter boundary layer.

An instrument trailer parked on the boundary between the alfalfa and corn fields housed the recording equipment. It should be pointed out that the wintertime snowfield observations were made at the central alfalfa field sampling site when the field was completely covered by snow.

The cornfield was divided in half along the central instrument line. The corn rows in the northwest half were oriented in the northeast-southwest direction, while the southeast half of the field had the rows oriented in the northwest-southeast direction. In this way the southeasterly winds blew "down row," and northwesterly winds blew "cross row" to the central instrument line. This arrangement permitted a study of row orientation influence on "surface roughness." All the corn was of the same variety, Cornell M–10. The crop was uniformly fertilized and all seed drilled in 36-inch rows. Water was obtained from the nearby creek for irrigating the corn.

The alfalfa field has been in continuous sod for 5 years. It consists of a mixture of Narragansett alfalfa and bromegrass. It is usually harvested twice yearly for hay.

MATERIALS AND METHODS

Masts

In order to measure wind and temperature profiles within the internal boundary layer just above the earth's surface, masts (fig. 6) were constructed out of 1½-inch aluminum tubing with provision for mounting anemometers at distances of 10, 20, 40, 80, and 160 centimeters from the bottom, and thermocouples at 20, 40, 80, and 160 centimeters from the bottom. This spacing allows greater accuracy of profile measurement in the region near the surface. Each basic mast unit has numerous extensions that make it possible to maintain the lowest anemometer from 10 to 25 centimeters above the height of the surface. With growing plants, the surface height is taken to be the top of the plants. Placing the masts at such heights fulfills the condition that the lowest sensing elements should be high enough above the surface to "see" the complete surface, and yet low enough to measure wind gradients present near the surface.

Wind Profile Measurements

The wind profile measurements reported here are mean values taken over 5-minute "runs" with Sonoya rotating cup anemometers.[3] In these instruments, for every seven revolutions of the cups, an electrical contact in the base of each instrument is momentarily closed, sending an

[3] The use of this or other patented equipment in this study does not imply approval of the product to the exclusion of others that may also be suitable.

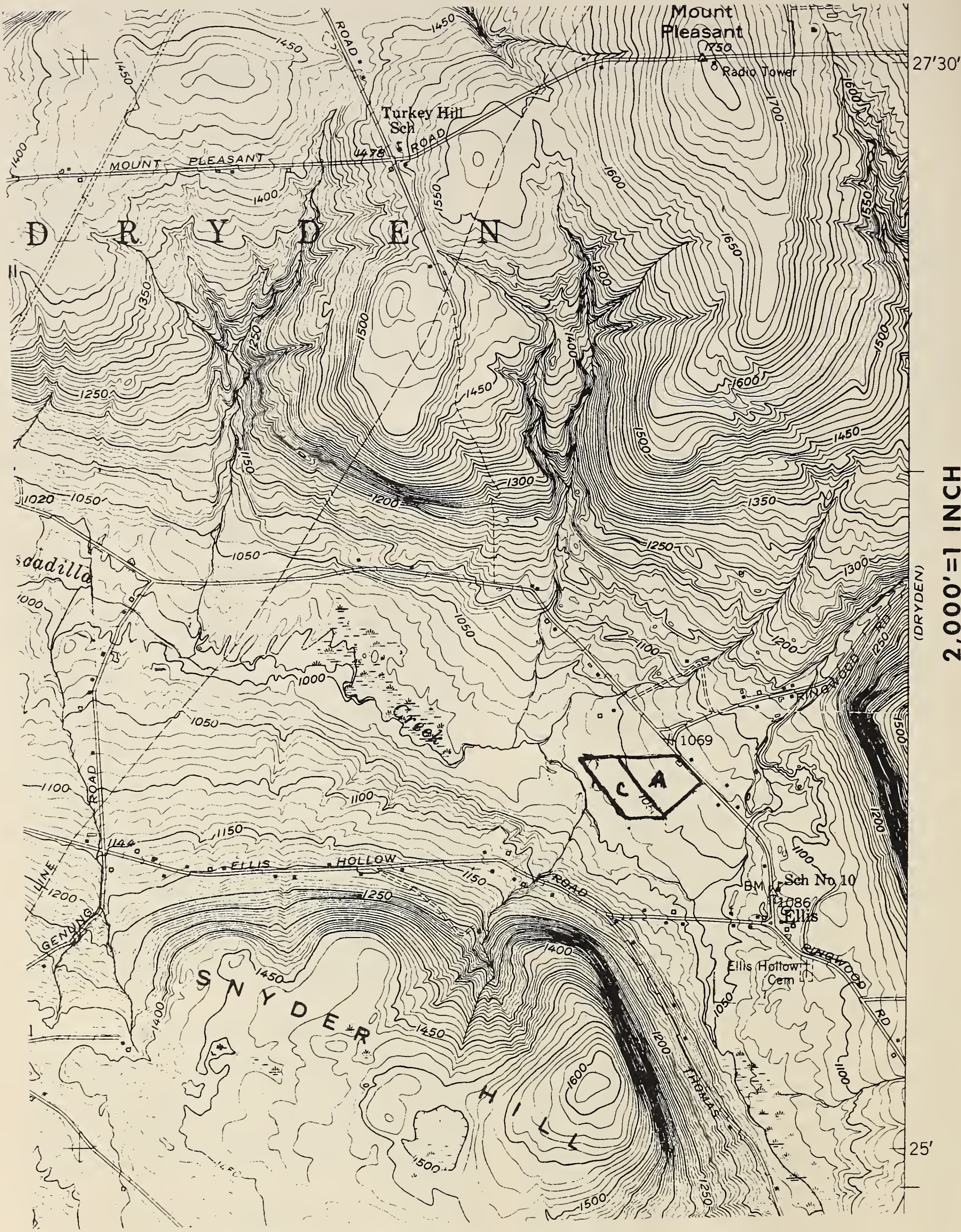

FIGURE 4.—Location of experimental site near Ithaca, N.Y.

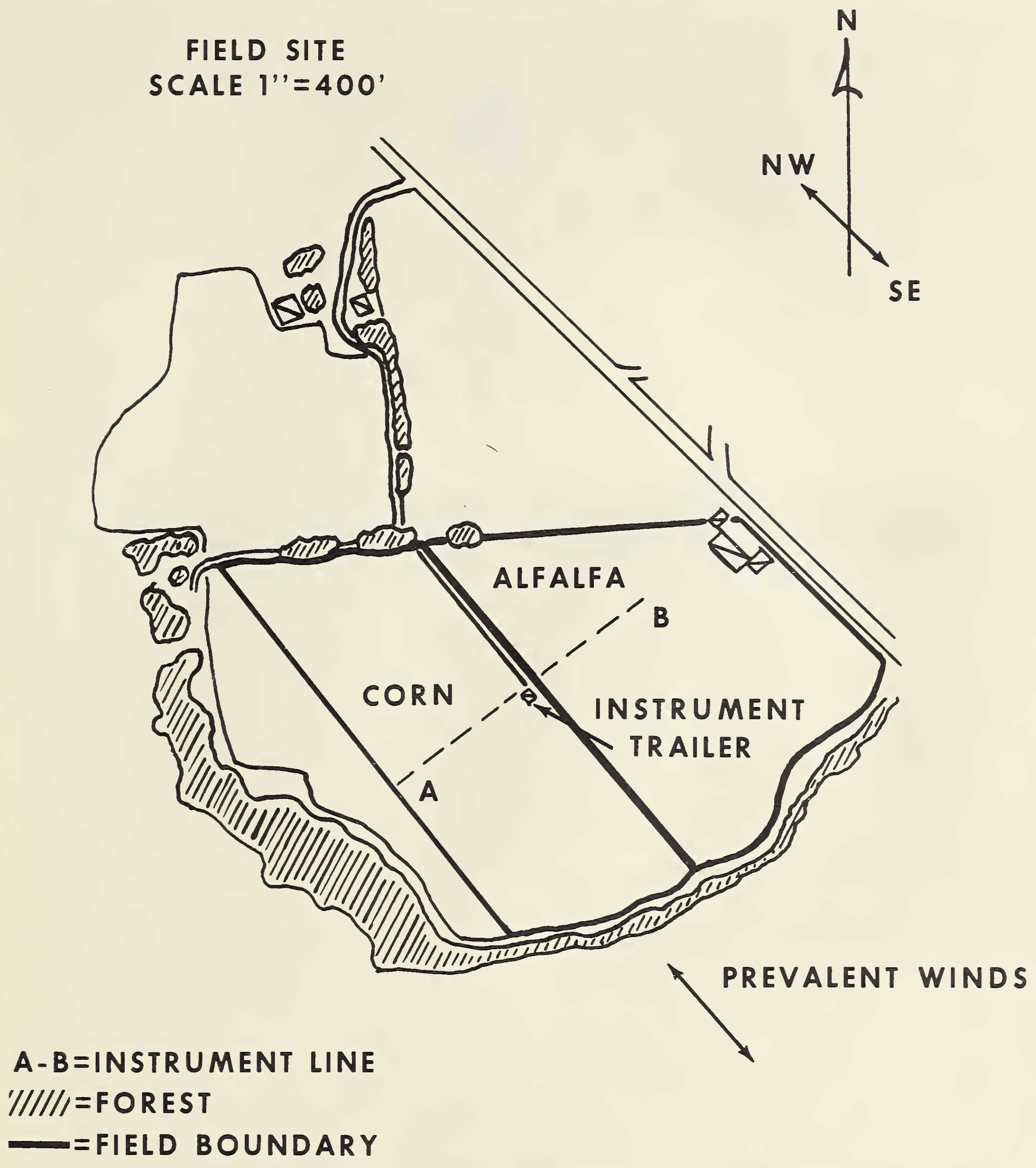

FIGURE 5.—Enlarged map of field experimental site—1 inch equals 400 feet.

impulse to a remote recording center where the impulse registers on a mechanical counter.

The anemometers are periodically tested in a wind tunnel for calibration. Those units that do not agree with the manufacturer's calibration in the range of 100 to 1,000 centimeters per second are eliminated from experimental use. It should be pointed out that the original calibrations are very nearly identical, so that the anemometers can be considered to be "matched."

Temperature Profile Measurements

The differential thermal gradient measuring system is a design by C. B. Tanner and E. R. Lemon. It consists of five junction copper-constantan thermopiles installed in thermometer bulbs at four locations on the masts, with a common reference junction located midway up the mast.

Figure 6 shows how the mast assembly acts as a manifold for the thermocouple aerating system.

FIGURE 6.—Temperature profile and wind profile mast assemblies.

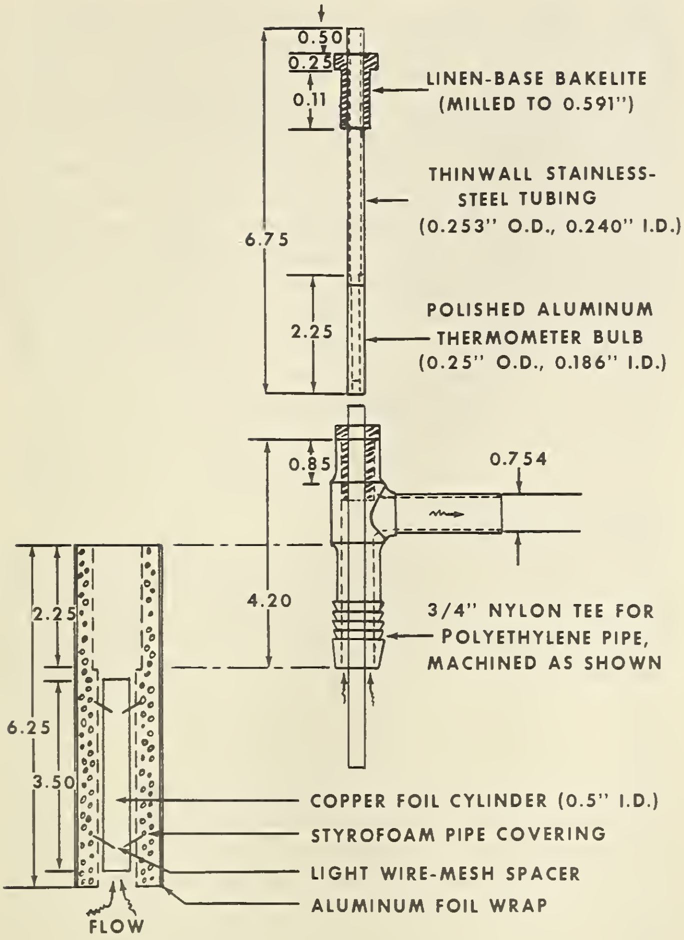

FIGURE 7.—Scale drawing of thermocouple housing. All measurements in inches.

Atop the mast a small blower exhausts the air, which in turn, is drawn through the thermocouple "nozzles," the supporting side arms, and the central mast. The blower delivery of 100 cubic feet per minute is great enough to insure thermal equilibrium between the ambient air and the four individual thermal sensing elements.

Figure 7 is a scale drawing of the thermocouple "nozzle" that includes the thermometer bulb and radiation shielding. The thermometer bulbs are made of polished, thick-walled (0.064-inch) aluminum tubing attached to thin-walled (0.013-inch) stainless steel tubing. The use of stainless steel as suspending stems minimizes heat conduction along the stem, whereas the aluminum tubing acts as a good heat conductor between the enclosed thermocouples and the ambient air stream. The stainless steel stem is positioned by a bakelite plug, machined to fit concentrically into a nylon plumbing tee by which the nozzle is attached to the mast unit.

The inner radiation shield is made from 0.002-inch copper foil, which is concentrically positioned between the thermometer bulb and the outer radiation shield with wire mesh. The foil is coated with Ebonal C to produce a flat, black surface. This thin shield acts as a radiation sink to be kept at thermal equilibrium by the passing airstream.

The outer radiation shield consists of a section of styrofoam pipe covering with a layer of aluminum foil cemented over the styrofoam. The inner and outer radiation shields are concentrically positioned over the thermometer bulb and attached to the nylon plumbing tee. Each five-junction thermopile is insulated with potting compound and inserted into the thermometer bulb along with 25 drops of transformer oil. The transformer oil aids in establishing thermal equilibrium between the thermopile and the thermometer bulb. The time constant for each unit is 2 minutes. It is important in such work that all units have identical time constants.

Tygon tubing encloses the thermopile wires from the top of each thermometer stem to the common reference junction. (Tygon has proved to be a poor material, as it breaks down in sunlight.) At the common reference junction, all thermopile reference junctions are insulated and potted together in an aluminum plug, 2 inches long by ¾-inch in diameter, insulated with styrofoam pipe covering and aluminum foil. The reference junction has a time constant of 2 hours. All thermopile measurements are differentials relative to the common reference temperature to an accuracy of ±0.02° C.

The differential millivolt signals are recorded on a fast response recording potentiometer (General Electric, Type CE Photoelectric Recorder). The recording potentiometer is connected through a gold contact selector switch by shielded copper leads to the differential thermopile system.

Wind and temperature profile measurements were usually made during 5-minute sampling periods. For such a "run" the potentiometer chart speed is increased so that several temperature profiles can be recorded in rapid succession by manual rotation of the selector switch. The temperature gradients are finally averaged for each 5-minute period.

Radiation Measurements

Net radiation is measured with a Beckman & Whitley portable net exchange radiometer, Model N188–1, placed upon a tripod approximately 4 meters high. Short wave solar and reflected radiation are measured by two 10-junction type Eppley pyrheliometers placed back to back, normal to the earth's surface, on a long arm extending from another 4-meter tripod.

In this study radiation was measured either continuously during the day on which heat budget data were taken or before and after each 5-minute wind and temperature profile run. Continuous recording of radiation was possible later in the summer season of 1959, when a 16-point Leeds

and Northrup recording potentiometer became available.

Soil Heat Flux Measurements

Soil heat flux was measured with six National Instrument Laboratories' heat-flow disks, Model HF–1–C, wired in parallel, and placed 10 inches apart across two northeast-southwest oriented corn rows. The six units were also spaced 10 inches apart in the alfalfa during the winter months. They were buried in the soil to a depth of 1 centimeter in both the corn and the alfalfa. The millivolt signal from these units was recorded on either of the two potentiometers mentioned above, depending upon the period in the season.

Determination of Wind Profile Parameters

A graphical or a statistical method may be used to determine the wind profile parameters from the anemometer data, as has been explained in an earlier section of this report. Both visual and statistical methods were used in this work—the statistical method when minor errors existed in the profile, and the visual method when there was considerable deviation in one of the two upper anemometer readings.

In the visual method considerably more weight was given to the lower anemometer readings, and in some cases only four of the five measurements were used when one of the two upper anemometer measurements was erratic.

Since the experimental site provides only a limited "fetch" over homogeneous surfaces, a survey of the wind profile in both the vertical and horizontal directions was made over the cornfield. Figure 8 presents the ratio of the windspeed, u_x, at various distances from the southwestern border to the windspeed at the central sampling site, u_{600}, for three anemometer heights above the ground surface (380, 430, and 530 centimeters). Measurements were made when the corn was 250 centimeters high, and the wind was from the southeast at 100 to 350 centimeters per second at the central site. The procedure involved making simultaneous 5-minute wind runs with a fixed mast and a portable mast. The portable mast was positioned at successive 100-foot intervals along the southeast-northwest axis of the cornfield. The data demonstrate the influence of the scattered trees on the borders. It appears, however, that most of the border effects are damped out, within the airstream measured, at a distance of 400 feet from the borders.

A vertical survey up to 7 meters above the ground demonstrated that border effects on the normal wind profile became apparent, however, in the airstream above 6 meters at the central sampling site. The vertical survey also demonstrated that the normal wind profile extended down to within 25 centimeters of the top of the corn plants. Thus, one concludes that in using the log profile method of calculating aerodynamic exchange rates, measurements at the central site are restricted to a boundary layer approximately 3 to 4 meters deep above the corn crop surface. In making measurements over the alfalfa and snow, it was felt that if measurements were made within 2 meters of the crop or snow surface, no abnormalities in the log profiles due to the borders should appear. Such was the case.

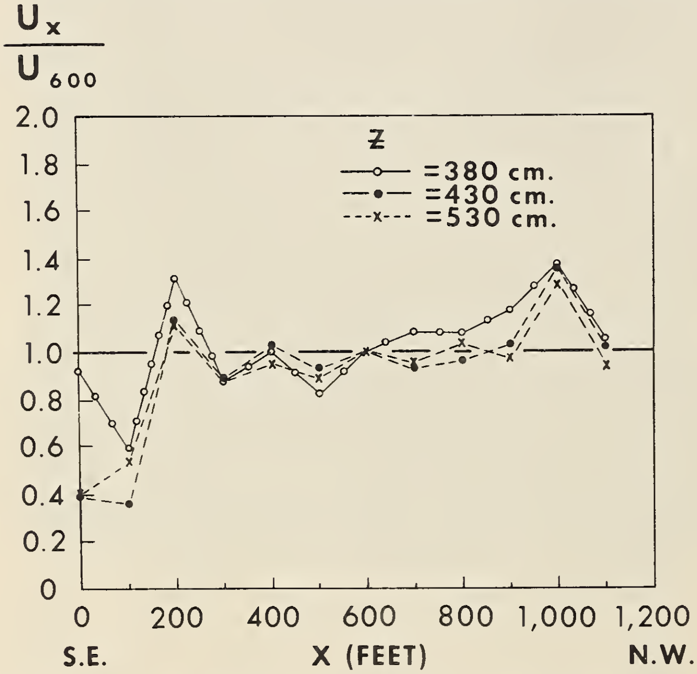

FIGURE 8.—The ratio of windspeed at three levels in the airstream above cornfield at x distance from southeast leading edge (u_x) to windspeed at central site (u_{600}).

Moisture Measurements

The moisture status of the soil-crop system ultimately determines the amount of evaporation and transpiration. Two methods were used to obtain quantitative information about the plant and soil moisture status.

Soil moisture tension was measured with tensiometers (Prosser Co.'s Irrometer, Model R) buried to 12- and 24-inch depths in three replicated batteries, so spaced across the cornfield as to give a representative sampling of the whole field. No tensiometers were placed in the alfalfa.

Since soil moisture tension is the force that plants must overcome to obtain water for their own use, it should closely correlate with the plant moisture status. Measurements of the latter phenomenon are less standardized. However, the measurement that was used and that is known to be closely related to diffusion pressure deficit in green plants gives what is called the relative turgidity of plant tissue. In this measurement, the mass of water in the plant when partially turgid (field, or fresh weight, minus dry weight) is expressed as a percentage of the mass of water in the plant when it is fully turgid (turgid weight

minus dry weight). By (1) cutting disk samples from actively growing mature leaves; (2) obtaining fresh weight immediately; (3) floating them on water under light for 6 hours; (4) blotting and weighing for turgid weight; and then (5) drying the sample for the dry weight, one can obtain fairly easily the moisture status of the plant. Sampling errors were kept minimal by cutting disks from 30 corn plants for each sample, and taking 6 samples so spaced as to represent the whole cornfield. No leaf turgor measurements were made in the alfalfa.

DATA ANALYSES

Energy Balance

Unfortunately, no accounting of the photosynthesis part of the heat budget was made in 1959. The infrared carbon dioxide analyzer borrowed in the previous years for such studies was not available. As a consequence, the heat budget equation used here does not contain the photosynthetic term (see equation 1).

$$R_n - S - H = E \tag{14}$$

In this report, the left-hand terms in the above equation were measured and E solved by difference; thus, E includes all the random errors inherent in the other measurements plus the error due to the omission of photosynthesis. The latter error could cause a 5 to 10 percent overestimation of E during active crop growth.

In all cases, the days selected for heat budget studies were clear days with few clouds. This type of day is invariably characterized in the Ithaca area by northwest winds, low humidity, and cool weather after a warmer, more humid period. Most of the summer days selected followed a rainy period so that moisture was plentiful.

Figure 9 presents the precipitation, soil moisture tension, and leaf turgor patterns in corn for the summer growing season. Also marked on the figure are the days on which heat budget data were obtained. It is obvious that timely rains and irrigation prevented any appreciable soil moisture tension or loss of turgor in the corn leaves during the growing season. There was no evidence to suggest that soil moisture was deficient in the alfalfa during heat budget studies in this crop, either.

The late arrival of the tensiometers did not allow measurements before July 7, but two distinct drying cycles are evident after this date. The first cycle was ended suddenly by a 2-inch irrigation, and the second was ended gradually by timely rains. As would be expected, tension in the 24-inch zone of the soil lagged behind the soil above it, and remained lower throughout the season. Only one battery of tensiometer data is plotted, since there was close agreement between replications.

The relative turgor curve on figure 9 shows that, in general, the turgidity of plants followed soil moisture tension, although the plants exhibited quite a bit more resistance to sudden change. It would be very difficult to read any error limitations into the relative turgor curve. Since it is a "relative" expression of plant turgor, it may only approximate field conditions. It is significant that under a stress of one atmosphere soil tension, the plant turgor never dropped to less than 80 percent of full turgor.

Tables 1 to 18 give the individual daily heat budget and radiation balance data. As mentioned above, the latent heat term, E, was solved by difference in equation 1. In all cases, H was determined aerodynamically by incorporating thermal and wind gradient data in equation 8b.

The seasonal trends of the heat budget components are plotted in figure 10. The trends are what one might expect. The corn was planted in late May so that the June 9 study represents a nearly bare soil with plants only a few inches high. Since the soil surface was dry, it is no surprise that sensible heat exchange with both the air and the soil accounted for most of the net radiation received. The latent heat term was consequently small. The trends in the heat budget for the season were most influenced by the increasing leaf area from the time that the crop emerged (about June 1) until full leaf development was complete (about August 1, when tasseling occurred). Full leaf development in a corn crop does not mean complete radiation interception by the plant leaves by any manner or means. Considerable radiation reaches the soil surface. This no doubt accounts for considerable sensible heat exchange with the air and soil and a consequent lower latent heat exchange than otherwise would be the case. This point is obvious in making comparisons between the corn and the alfalfa.

The measured sensible heat exchange with the air demonstrated that the alfalfa was losing from one-half to one-quarter that lost from the corn on July 8 and 9. The difference in the latent heat terms for the two crops is not a reliable comparison, because it was possible only to estimate soil heat flux in the alfalfa at this time. Nonetheless, the alfalfa was a lush crop, capable of intercepting much more radiation in the leaves than was the case of the corn on July 8 or July 9 (or even later, when the corn was in full leaf). Coupling this information with the fact that less sensible heat was exchanged by the alfalfa, one concludes that the latent heat term in the alfalfa should be greater than that in the corn, and that the differences which were calculated are probably of the correct order of magnitude.

The measurements in the corn in late July and early August should be fairly representative of the

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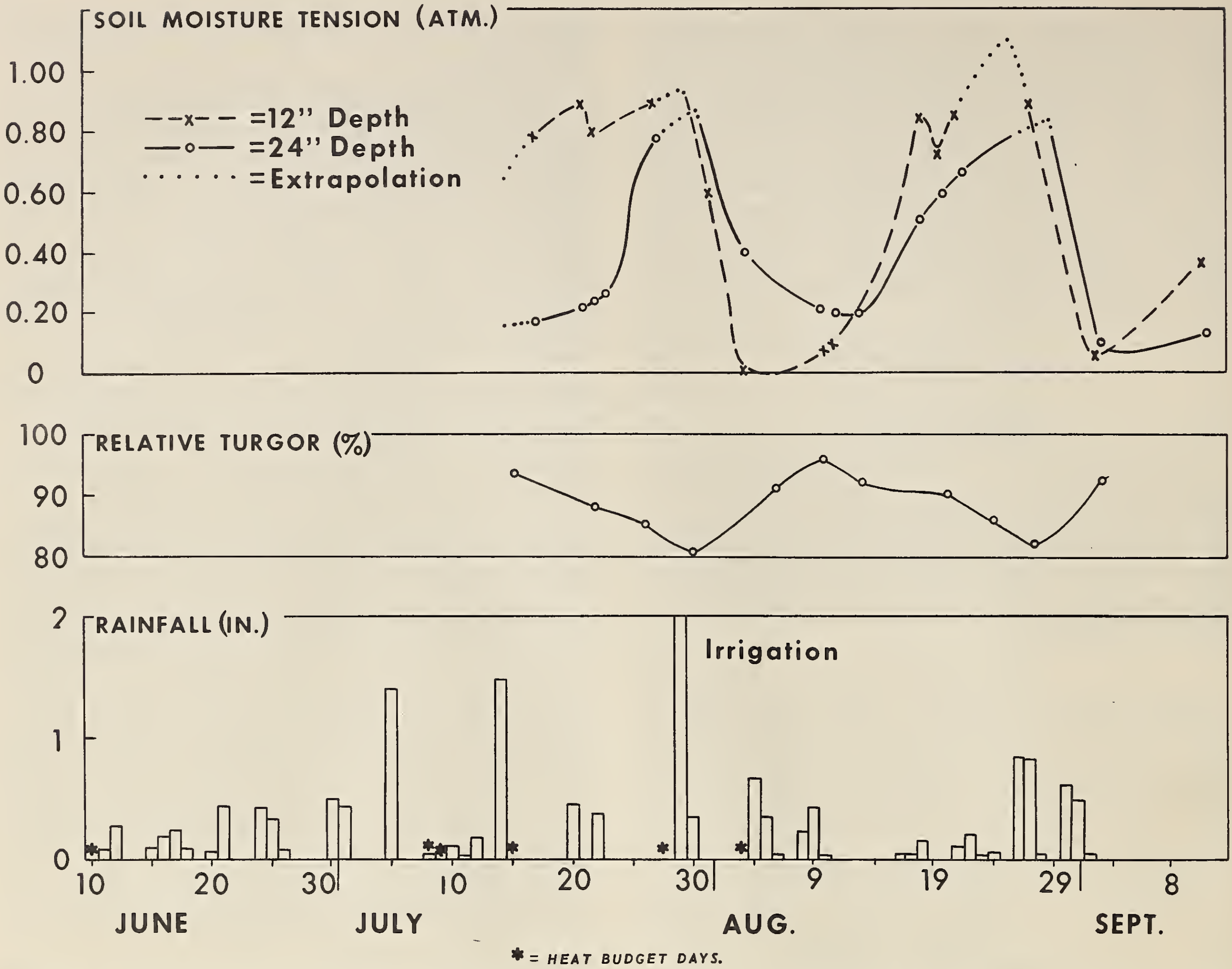

FIGURE 9.—Seasonal trend of rainfall, soil moisture tension, and plant (corn) turgor for summer 1959. "Heat budget" study days are also indicated.

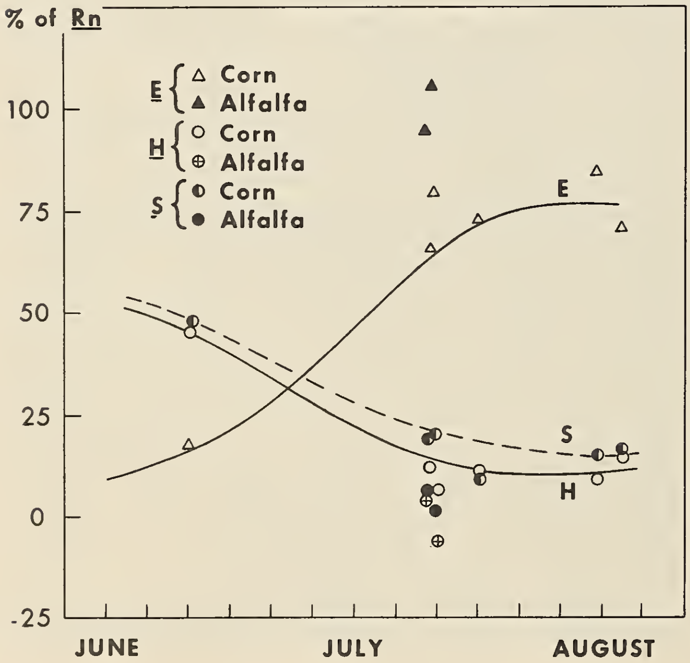

FIGURE 10.—Seasonal trend of daytime heat budget components in alfalfa and corn for summer 1959: E is percentage of net radiation (R_n) going into evapotranspiration (latent heat); S is percentage of R_n going into soil heat storage; H is percentage of R_n going into sensible heat exchange with the atmosphere.

crop for the rest of the season, since it had gained its full leaf status by this time. It should be pointed out that the heat budget did not change much between the July 27 measurements and the August 2 measurements, even though moisture stress appeared in both the soil and plant moisture measurements before the July 30 irrigation. If anything, the latent heat term appears to be larger before irrigation than after. These differences are no doubt within experimental error, however.

The heat budget over snow serves to emphasize the influence of the high surface reflectivity in preventing any net gain in energy at the earth's surface, even though the solar radiation received

on March 3, 1960, was comparable to that in the cornfield on July 9. It should be pointed out that under the snow blanket of nearly 2 feet no soil heat exchange could be detected. No accounting of the heat storage in the snow was made, however.

TABLE 1.—*Wind and temperature profile data for corn, Ithaca, N.Y., June 9, 1959* [1]

Time	D	Z at— 30 cm.		40 cm.		60 cm.		100 cm.		180 cm.		Δ u [2]	Δ T [2]
		u	T	u	T	u	T	u	T	u	T		
E.s.t.	*Cm.*	*Cm./sec.*	*° C.*	*Cm./sec.*	*° C.*	*Cm./sec.*	*° C.*	*Cm./sec.*	*° C.*	*Cm./sec.*	*° C.*	*Cm./sec.*	*° C.*
0517	10	10	0.8	60	--------	125	0.9	120	1.1	150	1.5	115	−0.10
0545	10	10	0	85	--------	100	.1	110	.2	160	.45	90	−.10
1617	10	20	0	105	--------	150	0	130	0	190	0	130	0
1737	5	100	2.3	140	--------	160	2.0	210	1.8	200	.7	60	.30
0830	5	40	3.3	140	--------	165	3.5	170	2.8	210	1.8	125	.20
0927	5	200	3.3	270	--------	360	2.8	395	1.4	460	1.1	160	.50
1005	5	110	3.2	220	--------	250	2.6	298	2.4	310	.9	140	.60
1030	5	180	2.7	315	--------	375	2.3	415	1.4	445	−.5	195	.50
1111	5	220	2.5	300	--------	370	2.0	410	1.7	460	−.1	210	.50
1200	5	120	3.2	230	--------	300	2.5	335	2.0	365	.1	180	.70
1251	5	220	3.0	300	--------	375	2.3	400	1.6	465	−.3	155	.70
1350	5	180	3.0	240	--------	280	2.4	330	2.0	375	−.6	100	.60
1448	5	250	2.8	320	--------	400	2.3	450	1.4	510	−.5	150	.30
1621	5	110	3.2	150	--------	240	2.3	250	2.5	260	1.6	130	.30
1745	--------	--------	2.8	--------	--------	--------	2.6	--------	2.3	--------	2.1	--------	--------
1910	--------	--------	2.1	--------	--------	--------	2.0	--------	1.9	--------	1.5	--------	--------

[1] u=wind velocity; T=temperature; Z=height above surface; D=effective displacement.
[2] $\Delta \overline{u}$ and $\Delta \overline{T}$ at Z_1=60 cm. at Z_2=30 cm.

TABLE 2.—*Wind and temperature profile data corn, Ithaca, N.Y., July 8, 1959* [1]

Time	D	Z at— 110 cm.		120 cm.		140 cm.		180 cm.		260 cm.		Δ u [2]	Δ T [2]
		u	T	u	T	u	T	u	T	u	T		
E.s.t.	*Cm.*	*Cm./sec.*	*° C.*	*Cm./sec.*	*° C.*	*Cm./sec.*	*° C.*	*Cm./sec.*	*° C.*	*Cm./sec.*	*° C.*	*Cm./sec.*	*° C.*
0543	60	110	1.15	120	--------	*130	*1.10	180	1.10	210	1.05	100	0.10
0630	60	120	.4	*130	--------	*140	.2	195	*.4	225	.3	105	.10
0755	50	210	1.8	220	--------	*235	1.7	280	*1.9	230	1.5	120	.30
0900	50	*235	2.5	*240	--------	245	2.4	295	*2.2	355	2.2	140	.30
1002	50	270	1.35	*270	--------	*275	*1.0	330	.95	375	.8	130	.55
1100	60	170	1.85	180	--------	210	1.55	260	1.35	300	*1.25	130	.60
1200	50	230	1.85	245	--------	*255	1.80	320	1.70	365	1.6	135	.25
1300	50	290	1.9	300	--------	*310	1.65	375	*1.3	425	1.3	135	.60
1400	50	*245	1.95	*250	--------	255	*1.7	315	1.65	390	1.45	170	.50
1500	50	*220	2.9	*225	--------	230	2.8	270	*2.8	330	2.6	140	.30
1600	50	*200	3.1	200	--------	*210	3.0	260	*3.2	310	3.0	130	.30
1700	50	200	3.8	205	--------	215	3.6	275	*3.6	310	3.6	110	.20
1820	60	95	3.8	120	--------	150	3.8	165	3.8	195	3.8	100	0
1900	--------	--------	3.7	--------	--------	--------	3.9	--------	4.0	--------	4.1	--------	.40
2000	--------	--------	1.45	--------	--------	--------	1.55	--------	1.55	--------	1.6	--------	−.15
2030	--------	--------	.8	--------	--------	--------	.85	--------	.90	--------	.35	--------	.15

[1] u=wind velocity; T=temperature; Z=height above surface; D=effective displacement; *=erratic data not included in exchange calculations.
[2] $\Delta \overline{u}$ and $\Delta \overline{T}$ at Z_1=260 cm. at Z_2=110 cm.

TABLE 3.—*Wind and temperature profile data for alfalfa, Ithaca, N.Y., July 8, 1959* [1]

Time	D	Z at— 46 cm. u	46 cm. T	56 cm. u	56 cm. T	76 cm. u	76 cm. T	116 cm. u	116 cm. T	196 cm. u	196 cm. T	Δ u [2]	Δ T [2]
E.s.t.	*Cm.*	*Cm./sec.*	*° C.*	*Cm./sec.*	*° C.*	*Cm./sec.*	*° C.*	*Cm./sec.*	*° C.*	*Cm./sec.*	*° C.*	*Cm./sec.*	*° C.*
0544	10	140	1. 6	*145		145	1. 5	*140	1. 35	150	1. 15	10	0. 55
0755	20	215	2. 9	225		280	2. 7	320	*2. 8	380	2. 4	180	. 50
0900	20	190	2. 9	*200		225	3. 0	280	2. 8	330	2. 6	180	. 70
1002	20	295	2. 05	320		330	*2. 1	440	2. 0	480	1. 95	240	. 10
1100	20	*240	1. 7	255		290	*1. 7	330	*1. 7	*360	1. 5	155	. 20
1200	20	235	*1. 65	245		280	1. 75	340	1. 65	*350	1. 5	190	. 35
1300	20	*240	1. 1	245		300	1. 0	365	*1. 05	*385	. 9	230	. 20
1400	20	*315	*1. 5	330		380	1. 45	450	1. 35	*480	1. 25	235	. 30
1500	20	*235	2. 0	235		280	2. 5	340	2. 3	*350	2. 6	205	. 45
1600	20	*190	2. 3	190		235	2. 5	190	2. 6	*300	2. 8	195	—. 50
1700	20	*220	2. 7	225		260	3. 2	285	3. 4	*345	3. 7	195	—1. 0
1820	10	*130	2. 6	140		170	*3. 0	225	3. 2	*210	3. 4	170	—. 90
1900			3. 7				3. 9		4. 0		4. 1		—. 40
2000			—. 1				1. 2		1. 6		2. 0		—2. 1
2030			—. 8				. 5		. 75		1. 0		—1. 2

[1] u=wind velocity; T=temperature; Z=height above surface; D=effective displacement; *=erratic data not included in exchange calculations.

[2] $\Delta \bar{u}$ and $\Delta \bar{T}$ at Z_1=196 cm.
at Z_2=46 cm.

TABLE 4.—*Wind and temperature profile data for corn, Ithaca, N.Y., July 9, 1959* [1]

Time	D	Z at— 110 cm. u	110 cm. T	120 cm. u	120 cm. T	140 cm. u	140 cm. T	180 cm. u	180 cm. T	260 cm. u	260 cm. T	Δ u [2]	Δ T [2]
E.s.t.	*Cm.*	*Cm./sec.*	*° C.*	*Cm./sec.*	*° C.*	*Cm./sec.*	*° C.*	*Cm./sec.*	*° C.*	*Cm./sec.*	*° C.*	*Cm./sec.*	*° C.*
0507	60	130	—0. 3	135		150	0. 05	205	0. 15	235	0. 20	105	—0. 50
0602	60	140	—1. 1	145		155	—. 95	210	*—. 80	245	—. 80	105	—. 30
0640	60	120	*1. 8	125		120	1. 8	*185	1. 85	195	1. 9	75	. 20
0800	50	*215	2. 3	200		220	2. 15	270	2. 05	315	*2. 2	125	. 30
0900	50	205	2. 25	*210		215	2. 1	280	1. 95	*315	*1. 95	155	. 30
1000	50	185	2. 15	210		230	1. 85	285	*2. 0	330	1. 70	145	. 30
1100	50	210	2. 0	225		235	*1. 8	300	1. 8	340	1. 75	130	. 25
1200	50	195	2. 1	205		225	*1. 9	265	2. 0	195	1. 9	100	. 20
1300	50	240	2. 7	255		275	*2. 7	295	2. 7	*350	2. 5	90	. 20
1400	50	355	2. 4	345		355	*2. 4	410	2. 23	440	*2. 4	85	. 25
1500	50	310	2. 5	320		325	*2. 5	380	*2. 4	*400	2. 5	125	. 10
1600	60	200	2. 9	210		220	*2. 9	255	*2. 6	300	2. 8	100	. 10

[1] u=wind velocity; T=temperature; Z=height above surface; D=effective displacement; *=erratic data not included in exchange calculations.

[2] $\Delta \bar{u}$ and $\Delta \bar{T}$ at Z_1=260 cm.
Z_2=110 cm.

TABLE 5.—*Wind and temperature profile data for alfalfa, Ithaca, N.Y., July 9, 1959* [1]

Time	D	Z at— 46 cm. u	46 cm. T	56 cm. u	56 cm. T	76 cm. u	76 cm. T	116 cm. u	116 cm. T	196 cm. u	196 cm. T	Δ u [2]	Δ T [2]
E.s.t.	*Cm.*	*Cm./sec.*	*° C.*	*Cm./sec.*	*° C.*	*Cm./sec.*	*° C.*	*Cm./sec.*	*° C.*	*Cm./sec.*	*° C.*	*Cm./sec.*	*° C.*
0507	10	90	−1. 1	115	--------	*120	−0. 5	*185	0. 10	200	*0. 40	110	−1. 5
0602	10	100	. 5	125	--------	*130	. 75	*195	1. 2	210	1. 3	110	−. 80
0800	20	200	2. 5	230	--------	*255	2. 65	325	2. 5	*330	2. 7	*180	−. 20
0900	10	*170	1. 8	170	--------	205	2. 1	*265	1. 75	*265	2. 0	145	−. 20
1000	20	*225	1. 75	*280	--------	345	1. 65	410	1. 7	*480	1. 7	220	+. 05
1100	20	225	2. 2	255	--------	310	2. 2	370	2. 2	420	*2. 3	195	0
1200	10	*155	1. 95	170	--------	215	2. 05	260	2. 0	*270	2. 2	180	−. 25
1300	20	220	2. 7	240	--------	255	2. 7	320	3. 1	*340	3. 3	150	−. 60
1400	20	270	2. 6	310	--------	350	2. 7	410	3. 2	475	3. 3	205	−. 70
1500	20	215	2. 0	*225	--------	290	2. 4	335	2. 3	370	2. 8	155	−. 80
1600	10	180	2. 1	210	--------	255	2. 8	*275	2. 8	*295	3. 3	185	−1. 20

[1] u=wind velocity; T=temperature; Z=height above surface; D=effective displacement; *=erratic data not included in exchange calculations.
[2] $\Delta \bar{u}$ and $\Delta \bar{T}$ at Z_1=196 cm.
Z_2=46 cm.

TABLE 6.—*Wind and temperature profile data for corn, Ithaca, N.Y., July 15, 1959* [1]

Time	D	Z at— 190 cm. u	190 cm. T	200 cm. u	200 cm. T	220 cm. u	220 cm. T	260 cm. u	260 cm. T	340 cm. u	340 cm. T	Δ u [2]	Δ T [2]
E.s.t.	*Cm.*	*Cm./sec.*	*° C.*	*Cm./sec.*	*° C.*	*Cm./sec.*	*° C.*	*Cm./sec.*	*° C.*	*Cm./sec.*	*° C.*	*Cm./sec.*	*° C.*
0533	------	--------	0. 3	--------	--------	--------	0. 3	--------	0. 3	--------	0. 3	0	0. 00
0640	140	80	. 35	90	--------	85	*. 20	110	. 25	115	. 15	35	. 20
0718	130	90	*. 6	70	--------	100	. 65	125	. 55	140	. 50	50	. 20
0846	120	*230	*1. 8	*240	--------	240	1. 9	260	1. 7	295	*1. 7	80	. 60
0947	100	300	2. 15	320	--------	345	2. 00	*355	1. 8	420	1. 7	120	. 45
1054	110	275	1. 7	295	--------	300	1. 6	335	*1. 6	375	*1. 6	100	. 40
1218	120	210	1. 9	215	--------	230	*1. 5	260	1. 5	285	1. 3	75	. 60
1518	110	265	*2. 4	270	--------	275	2. 5	315	2. 3	365	*2. 3	100	. 45
1746	120	225	. 25	230	--------	245	. 25	265	. 30	*280	. 25	75	0
1802	100	345	. 50	355	--------	380	. 45	420	. 45	475	. 45	130	0

[1] u=wind velocity; T=temperature; Z=height above surface; D=effective displacement; *=erratic data not included in exchange calculations.
[2] $\Delta \bar{u}$ and $\Delta \bar{T}$ at Z_1=340 cm.
Z_2=190 cm.

TABLE 7.—*Wind and temperature profile data for corn, Ithaca, N.Y., July 27, 1959* [1]

Time	D	Z at—										Δu [2]	ΔT [2]
		265 cm.		275 cm.		295 cm.		335 cm.		415 cm.			
		u	T	u	T	u	T	u	T	u	T		
E.s.t.	*Cm.*	*Cm./sec.*	*° C.*	*Cm./sec.*	*° C.*	*Cm./sec.*	*° C.*	*Cm./sec.*	*° C.*	*Cm./sec.*	*° C.*	*Cm./sec.*	*° C.*
0551	200	10	−0. 3	15	--------	60	−0. 25	65	*−0. 03	70	*−0. 25	60	0. 15
0620	200	100	−. 1	*100	--------	130	*−. 1	145	−. 05	160	−. 03	60	. 07
0723	140	130	2. 25	140	--------	150	2. 3	160	2. 05	*165	*2. 15	40	. 20
0821	140	*180	2. 4	205	--------	210	*2. 4	230	*2. 2	245	2. 2	50	. 20
0925	140	200	2. 0	205	--------	225	*1. 9	240	1. 9	*270	*1. 9	55	. 22
1033	140	190	2. 25	195	--------	220	2. 2	225	2. 15	240	*2. 1	50	. 25
1112	130	240	2. 3	245	--------	265	*2. 1	290	2. 2	*340	2. 0	60	. 30
1249	140	120	*1. 2	145	--------	160	*1. 2	165	1. 2	*170	1. 1	85	. 30
1356	130	360	*2. 0	370	--------	395	2. 1	425	2. 0	*450	1. 9	110	. 25
1448	140	220	2. 9	230	--------	240	2. 8	245	*2. 8	*250	2. 6	50	. 30
1536	140	*230	*3. 1	220	--------	235	3. 3	245	3. 0	*250	3. 2	60	. 20
1710	140	190	2. 8	195	--------	210	*2. 8	225	2. 75	250	2. 7	60	. 10

[1] u=wind velocity; T=temperature; Z=height above surface; D=effective displacement; *=erratic data not included in exchange calculations.

[2] $\Delta \bar{u}$ and $\Delta \bar{T}$ at $Z_1=415$ cm.
$Z_2=265$ cm.

TABLE 8.—*Wind and temperature profile data for corn, Ithaca, N.Y., Aug. 2, 1959* [1]

Time	D	Z at—										Δu [2]	ΔT [2]
		270 cm.		280 cm.		300 cm.		340 cm.		480 cm.			
		u	T	u	T	u	T	u	T	u	T		
E.s.t.	*Cm.*	*Cm./sec.*	*° C.*	*Cm./sec.*	*° C.*	*Cm./sec.*	*° C.*	*Cm/.sec.*	*° C.*	*Cm./sec.*	*° C.*	*Cm./sec.*	*° C.*
0515	------	--------	−0. 6	--------	--------	--------	−0. 58	--------	−0. 55	--------	−0. 53	--------	−0. 07
0618	200	0	2. 1	10	--------	20	2. 1	40	*2. 0	60	2. 1	60	0
0705	110	*225	3. 8	*225	--------	270	4. 0	290	*3. 9	320	3. 9	70	. 10
0801	120	*160	2. 15	*170	--------	200	2. 20	215	*2. 35	230	2. 35	40	. 20
0901	100	335	2. 5	345	--------	365	2. 4	395	2. 35	440	2. 2	105	. 30
1001	120	220	3. 0	225	--------	235	2. 8	255	2. 9	280	2. 7	60	. 30
1101	100	320	2. 4	325	--------	350	*2. 2	370	2. 25	400	2. 15	80	. 25
1208	100	290	2. 3	300	--------	320	*2. 0	360	2. 1	385	1. 8	95	. 40
1302	110	*230	1. 8	*245	--------	275	1. 7	280	1. 6	*300	*1. 55	70	. 40
1402	120	*155	2. 0	*175	--------	210	1. 95	225	1. 65	245	*1. 45	50	. 50
1502	120	*165	1. 5	*190	--------	225	1. 4	245	1. 35	280	1. 2	80	. 30
1602	110	295	2. 0	305	--------	320	1. 9	*360	1. 8	375	1. 7	80	. 30
1704	100	330	2. 2	335	--------	350	2. 1	320	*2. 2	425	2. 0	95	. 20
1802	120	185	2. 3	190	--------	230	*2. 2	240	2. 3	290	2. 3	105	0
1902	200	10	1. 8	10	--------	30	2. 0	50	2. 2	60	2. 4	50	−. 60

[1] u=wind velocity; T=temperature; Z=height above surface; D=effective displacement; *=erratic data not included in exchange calculations.

[2] $\Delta \bar{u}$ and $\Delta \bar{T}$ at $Z_1=480$ cm.
$Z_2=270$ cm.

TABLE 9.—*Wind and temperature profile data over field of snow, Ithaca, N.Y., Mar. 9, 1960* [1]

Time	*D*	*Z* at— 15 cm.		25 cm.		45 cm.		85 cm.		165 cm.		Δ *u* [2]	Δ *T* [2]
		u	*T*	*u*	*T*	*u*	*T*	*u*	*T*	*u*	*T*		
E.s.t.	*Cm.*	*Cm./sec.*	*° C.*	*Cm./sec.*	*° C.*	*Cm./sec.*	*° C.*	*Cm./sec.*	*° C.*	*Cm./sec.*	*° C.*	*Cm./sec.*	*° C.*
0644–59	10	*25	−0.41	165	-------	180	0.30	190	1.25	*180	2.2	40	−1.90
0703–18	10	*40	−.80	145	-------	185	0	195	.55	*180	2.05	30	−2.05
0802–17	10	50	2.1	*115	-------	100	3.0	120	*3.1	*105	4.35	40	−1.35
0842–57	10	30	3.8	70	-------	100	4.35	110	*4.0	*95	5.0	30	−.65
0921–36	0	430	5.6	*525	-------	515	4.2	575	4.3	630	4.75	100	−.55
1005–20	0	375	3.15	*450	-------	445	3.3	505	3.4	520	3.42	75	−.12
1117–32	0	330	2.25	*400	-------	390	3.1	-------	3.1	460	3.00	70	.10
1135–50	0	170	4.8	-------	-------	215	4.6	-------	4.4	250	4.35	45	.25
1245–00	0	300	3.75	*365	-------	350	3.95	-------	3.90	420	3.85	70	.10
1352–07	0	110	4.5	*150	-------	165	4.75	-------	4.70	200	4.60	40	.15
1447–02	0	235	*4.30	*300	-------	305	4.50	-------	4.50	335	4.50	30	0
1545–00	0	135	3.0	150	-------	*195	3.2	-------	3.30	230	3.40	55	−.20
1645–00	0	-------	4.0	-------	-------	-------	4.4	-------	4.7	-------	5.1	-------	−.70
1735–50	0	125	1.0	*200	-------	230	1.5	240	2.3	*305	*3.5	75	−1.50
2000–15	10	40	1.3	*70	-------	115	1.0	-------	1.45	125	1.35	35	−.95

[1] *u*=wind velocity; *T*=temperature; *Z*=height above surface; *D*=effective displacement; *=erratic data not included in exchange calculations.

[2] $\Delta \bar{u}$ and $\Delta \bar{T}$ at Z_1=165 cm.
at Z_2= 45 cm.

TABLE 10.—*Heat budget data for corn, Ithaca, N.Y., June 9, 1959* [1]

Time	*Rn* [2]	*Ri*	*Rr*	Time	*Rn*	*S*	*H*	*E*
E.s.t.		*Ly./min.*		*E.s.t.*	*Ly./min.*	*Ly./min.*	*Ly./min.*	*Ly./min.*
				0517	0.018	0.110	−0.0347	−0.0570
				0545	.041	.130	−.0253	−.0637
				0617	.190	.180	0	.010
				0737	.360	.200	.0734	.0866
				0830	.540	.330	.1017	.1083
				0927	.71	.360	.3256	.0304
				1005	.790	.364	.3418	.0842
				1030	.820	.390	.3988	.0312
		NO DATA		1111	.908	.390	.4273	.0907
				1200	.943	.390	.5130	.0400
				1251	.962	.440	.4415	.0805
				1350	.908	.390	.2442	.2738
				1448	.765	.250	.3036	.2114
				1621	.179	.120	.1587	.0997
				1745	.000	−.015	----------	----------
				1910	−.089	−.076	----------	----------

[1] *Rn*=net radiation received at surface of the earth; *Ri*=incoming solar radiation; *Rr*=reflected solar radiation; *S*=heat conducted into the soil; *H*=heat connected and conducted into the air-sensible heat; *E*=heat used in evaporating water-latent heat; *Ly.*=calories per square centimeter.

[2] See column 6, this table.

TABLE 11.—*Heat budget data for corn, Ithaca, N.Y., July 8, 1959* [1]

Time	*Rn*	*Ri*	*Rr*	Time	*Rn*	*S*	*H*	*E*
E.s.t.	*Ly./min.*	*Ly./min.*	*Ly./min.*	*E.s.t.*	*Ly./min.*	*Ly./min.*	*Ly./min.*	*Ly./min.*
0500	−0.224	0.15	0.18	0543	−0.08	−0.02	0.0131	−0.073
0600	−.027	.46	.33	0630	.02	.02	.0136	−.0136
0700	.061	.73	.40	0755	.367	.097	.0525	.218
0800	.367	.93	.46	0900	.618	.097	.0594	.462
0900	.618	1.12	.52	1002	.636	.088	.0930	.455
1000	.636	1.20	.55	1100	.752	.094	.1032	.555
1100	.752	1.32	.55	1200	.815	.091	.0543	.669
1200	.815	1.39	.55	1300	.743	.097	.1305	.52
1300	.743	1.24	.55	1400	.725	.094	.0630	.568
1400	.725	1.22	.55	1500	.582	.114	.0545	.414
1500	.582	1.05	.53	1600	.421	.097	.0533	.271
1600	.421	.98	.49	1700	.295	.081	.0354	.178
1700	.295	.77	.40	1820	.000	.081	0	0
1800	.063	.50	.34	1900	−.081	.050	---	---
1900	−.081	.43	.17	2000	---	---	---	---
2000	---	0	0	2030	---	---	---	---

[1] *Rn*=net radiation received at surface of the earth; *Ri*=incoming solar radiation; *Rr*=reflected solar radiation; *S*=heat conducted into the soil; *H*=heat connected and conducted into the air-sensible heat; *E*=heat used in evaporating water-latent heat; *Ly.*=calories per square centimeter.

TABLE 12.—*Heat budget data for alfalfa, Ithaca, N.Y., July 8, 1959* [1]

Time	*Rn*	*Ri*	*Rr*	Time	*Rn* [2]	*S* [2]	*H*	*E*
E.s.t.	*Ly./min.*			*E.s.t.*	*Ly./min.*	*Ly./min.*	*Ly./min.*	*Ly./min.*
	SEE TABLE 11			0544	0.215	−0.010	0.0042	0.22
				0755	.525	.010	.0624	.45
				0900	.700	.048	.0927	.56
				1002	.807	.048	.023	.74
				1100	.944	.044	.022	.88
				1200	1.005	.047	.046	.91
				1300	.875	.045	.032	.80
				1400	.805	.048	.049	.71
				1500	.623	.047	−.064	.64
				1600	.462	.055	−.067	.47
				1700	.294	.048	−.135	.38
				1820	.054	.040	−.124	.13
				1900	−.026	.040	---	---
				2000	---	---	---	---
				2030	---	---	---	---

[1] *Rn*=net radiation received at surface of the earth; *Ri*=incoming solar radiation; *Rr*=reflected solar radiation; *S*=heat conducted into the soil; *H*=heat connected and conducted into the air-sensible heat; *E*=heat used in evaporating water-latent heat; *Ly.*=calories per square centimeter.

[2] Estimated.

TABLE 13.—*Heat budget data for corn, Ithaca, N.Y., July 9, 1959* [1]

Time	*Rn*	*Ri*	*Rr*	Time	*Rn*	*S*	*H*	*E*
E.s.t.	*Ly./min.*	*Ly./min.*	*Ly./min.*	*E.s.t.*	*Ly./min.*	*Ly./min.*	*Ly./min.*	*Ly./min.*
0500	−0. 116	0. 27	0. 05	0507	−0. 105	0. 000	−0. 0684	−0. 0366
0600	−. 027	. 36	. 21	0602	−. 025	. 006	−. 0415	+. 0105
0700	. 170	. 58	. 34	0640	. 090	. 040	−. 0098	. 0600
0800	. 367	. 81	. 45	0800	. 367	. 097	. 0276	. 2424
0900	. 546	. 97	. 51	0900	. 546	. 114	. 0516	. 3804
1000	. 725	1. 20	. 55	1000	. 725	. 097	. 0405	. 5875
1100	. 922	1. 24	. 55	1100	. 922	. 130	. 0523	. 7397
1200	. 941	1. 24	. 55	1200	. 941	. 130	. 0322	. 7788
1300	. 904	1. 32	. 55	1300	. 904	. 097	. 0290	. 7780
1400	. 868	1. 20	. 53	1400	. 868	. 081	. 0320	. 7550
1500	. 734	1. 12	. 25	1500	. 734	. 081	. 0247	. 6283
1600	. 636	. 97	. 13	1600	. 636	. 081	. 0187	. 5363
1700	. 295	. 66	. 05					
1800	. 081	. 46	. 04					
1900								
2000								

[1] *Rn*=net radiation received at surface of the earth; *Ri*=incoming solar radiation; *Rr*=reflected solar radiation; *S*=heat conducted into the soil; *H*=heat connected and conducted into the air-sensible heat; *E*=heat used in evaporating water-latent heat; *Ly.*=calories per square centimeter.

TABLE 14.—*Heat budget data for alfalfa, Ithaca, N.Y., July 9, 1959* [1]

Time	*Rn*	*Ri*	*Rr*	Time	*Rn* [2]	*S* [2]	*H*	*E*
E.s.t.	*Ly./min.*			*E.s.t.*	*Ly./min.*	*Ly./min.*	*Ly./min.*	*Ly./min.*
				0507	0. 0520	−0. 005	−0. 176	0. 233
				0602	. 2174	. 003	−. 083	. 297
				0800	. 458	. 048	−. 025	. 435
				0900	. 714	. 055	−. 020	. 678
				1000	. 806	. 048	−. 010	. 748
	SEE TABLE 13			1100	. 893	. 065	. 000	. 828
				1200	. 893	. 065	−. 042	. 868
				1300	. 930	. 048	−. 063	. 945
				1400	. 792	. 040	−. 098	. 851
				1500	. 669	. 040	−. 087	. 716
				1600	. 458	. 040	−. 156	. 575

[1] *Rn*=net radiation received at surface of the earth; *Ri*=incoming solar radiation; *Rr*=reflected solar radiation; *S*=heat conducted into the soil; *H*=heat connected and conducted into the air-sensible heat; *E*=heat used in evaporating water-latent heat; *Ly.*=calories per square centimeter.

[2] Estimated.

TABLE 15.—*Heat budget data for corn, Ithaca, N.Y., July 15, 1959* [1]

Time	*Rn*	*Ri*	*Rr*	Time	*Rn*	*S*	*H*	*E*
E.s.t.	*Ly./min.*	*Ly./min.*	*Ly./min.*	*E.s.t.*	*Ly./min.*	*Ly./min.*	*Ly./min.*	*Ly./min.*
0500	−0.170	0.0000	---	0535	−0.160	−0.015	0.0000	−0.145
0600	.000	.2519	---	0640	.080	.020	.0092	.0508
0700	.125	.5503	---	0718	.180	.035	.0161	.1289
0800	.403	.8914	---	0846	.600	.064	.0933	.4427
0900	.716	1.2402	---	0947	.930	.060	.1416	.7284
1000	.994	1.4999	---	1054	1.040	.055	.1049	.8801
1100	---	---	---	1218	1.060	.030	.0876	.9424
1200	1.090	---	---	1518	.530	.030	.0875	.4125
1300	---	1.4340	---	1746	.060	0	0	.0600
1400	.931	1.4030	---	1802	0	0	0	0
1500	.564	.8720	---	---	---	---	---	---
1600	.089	.2829	---	---	---	---	---	---
1700	.178	.3953	---	---	---	---	---	---
1800	.009	.1395	---	---	---	---	---	---

[1] *Rn*=net radiation received at surface of the earth; *Ri*=incoming solar radiation; *Rr*=reflected solar radiation; *S*=heat conducted into the soil; *H*=heat connected and conducted into the air-sensible heat; *E*=heat used in evaporating water-latent heat; *Ly.*=calories per square centimeter.

TABLE 16.—*Heat budget data for corn, Ithaca, N.Y., July 27, 1959* [1]

Time	*Rn*	*Ri*	*Rr*	Time	*Rn*	*S*	*H*	*E*
E.s.t.	*Ly./min.*	*Ly./min.*	*Ly./min.*	*E.s.t.*	*Ly./min.*	*Ly./min.*	*Ly./min.*	*Ly./min.*
0500	---	0.31	0.03	---	---	---	---	---
0551	0.063	---	---	0551	0.063	0.065	−0.0133	−0.068
0600	.152	.47	.09	0620	.152	.065	−.0119	.157
0700	.403	.77	.17	0723	.492	.075	.0330	.384
0800	.618	1.05	.20	0821	.650	.098	.0463	.506
0900	.707	1.16	.22	0925	.800	.130	.0498	.621
1000	.940	1.35	.26	1033	.965	.098	.0575	.816
1100	.976	1.47	.29	1112	.990	.124	.0813	.785
1200	1.012	1.44	.27	1249	1.100	.082	.1051	.913
1300	1.003	1.35	.28	1356	.862	.088	.1196	.654
1400	.850	1.20	.27	1448	.630	.075	.0619	.493
1500	.707	1.05	.24	1536	.550	.072	.0495	.425
1600	.510	.82	.21	1710	.200	.059	.0257	.115

[1] *Rn*=net radiation received at surface of the earth; *Ri*=incoming solar radiation; *Rr*=reflected solar radiation; *S*=heat conducted into the soil; *H*=heat connected and conducted into the air-sensible heat; *E*=heat used in evaporating water-latent heat; *Ly.*=calories per square centimeter.

TABLE 17.—*Heat budget data for corn, Ithaca, N.Y., Aug. 2, 1959* [1]

Time	*Rn*	*Ri*	*Rr*	Time	*Rn*	*S*	*H*	*E*
E.s.t.	*Ly./min.*	*Ly./min.*	*Ly./min.*	*E.s.t.*	*Ly./min.*	*Ly./min.*	*Ly./min.*	*Ly./min.*
0500	−0.036	0.14	0.05	0515	−0.036	0.033	0.0000	−0.003
0600	−.045	.14	.05	0618	−.036	.033	0.0000	−.003
0700	.027	.19	.04	0705	.027	.033	−.0403	.034
0800	.170	.46	.14	0801	.179	.033	−.0421	.188
0900	.366	.73	.19	0901	.375	.049	.1874	.183
1000	.546	.96	.22	1001	.555	.065	.0938	.455
1100	.707	1.22	.25	1101	.716	.059	.1315	.579
1200	.832	1.30	.27	1208	.841	.179	.2500	.573
1300	.850	1.38	.26	1302	.859	.146	.1611	.552
1400	.904	1.42	.28	1402	.913	.146	.1323	.635
1500	.832	1.34	.26	1502	.841	.144	.1264	.571
1600	.671	1.19	.24	1602	.680	.130	.1474	.403
1700	.492	.96	.21	1704	.501	.049	.1249	.371
1800	.304	.76	.18	1802	.313	.065	0	.248
1900	−.081	.11	.04	1902	−.072	.026	−.0508	−.092

[1] *Rn*=net radiation received at surface of the earth; *Ri*=incoming solar radiation; *Rr*=reflected solar radiation; *S*=heat conducted into the soil; *H*=heat connected and conducted into the air-sensible heat; *E*=heat used in evaporating water-latent heat; *Ly.*=calories per square centimeter.

TABLE 18.—*Heat budget study over snow, Ithaca, N.Y., Mar. 9, 1960* [1]

Time	Rn	Time	Ri	Time	Rr	Time	H	Rn	E+S
E.s.t.	*Ly./min.*	*E.s.t.*	*Ly./min.*	*E.s.t.*	*Ly./min.*	*E.s.t.*	*Ly./min.*	*Ly./min.*	*Ly./min.*
01	−0.09								
02	−.08								
03	−.08								
04	−.08								
05	−.075								
06	−.070	0600	0.00	0600	0.00	0644	−0.0870	−0.045	−0.132
07	−.045	0700	.28	0700	.15	0703	−.0704	−.040	−.102
08	−.015	0800	.53	0800	.47	0802	−.0618	−.015	−.0768
09	.005	0936	.89	0936	.76	0842	−.0223	.005	−.0228
10	.050	1012	1.01	1012	.87	0921	−.0711	.040	−.0311
11	.055	1135	1.16	1135	.99	1005	−.0134	.050	.0366
12	.060	1250	1.24	1250	1.07	1117	.0105	.060	.0495
13	.025					1135	.0168	.060	.0432
14	−.030	1407	1.00	1407	.87	1245	.0105	.040	.0295
15	−.050	1500	.69	1500	.67	1352	.0089	−.03	−.0211
16	−.070	1558	.43	1558	.44	1447	0	−.05	−.0500
17	−.095	1700	.19	1700	.19	1545	−.0165	−.07	−.0865
18	−.050	1745	.04	1745	.04	1645	−.0105	−.07	−.0805
19	−.040	1905	0	1905	0	1735	−.1684	−.05	−.2184
20	−.065					2000	−.0380	−.04	−.0780
21	−.060								
22	−.060								
23	−.060								
24	−.050								

[1] *Rn*=net radiation received at surface of the earth; *Ri*=incoming solar radiation; *Rr*=reflected solar radiation; *S*=heat conducted into the soil; *H*=heat connected and conducted into the air-sensible heat; *E*=heat used in evaporating water-latent heat; *Ly.*=calories per square centimeter.

Wind Profile Characteristics

When the fact is recognized that the aerodynamic exchange equations used in this study are dependent upon wind profile characteristics over a crop surface and the winds in turn are conditioned by geometric and elastic properties of the surface, it seems advisable to look into the functional relationships involved.[4] Two studies of wind profiles (those approaching isothermal conditions) were made—(1) to determine the influence of corn crop maturity on the profile parameters and (2) to determine the influence of corn row orientation on the profile parameters. The corn maturity studies were made at the satellite station where the prevailing winds always blew perpendicular to the corn rows. The row orientation studies were necessarily made at the central station for reasons given earlier.

From graphical and statistical techniques explained in detail in the preceding section, the wind profiles were analyzed for the functional relationships of friction velocity, u^*; roughness length, z_0; surface drag, τ_0; and zero-plane displacement, d.

The wind profile measurements above the immature corn were made on July 18, 1959, when the corn was 180 centimeters high. Those made on the mature corn were obtained on three different days, July 27, August 1 and 2, 1959, when the corn was fully grown to 230 centimeters high. All the detailed data can be found in table 19.

Figures 11 and 12 and tables 20 and 21 present the relationships sought. In figure 11, the ratio of the friction velocity to Karman's constant, u^*/k (where $k=0.4$) is plotted against the roughness length, z_0, for the immature and mature corn. It is evident that roughness is directly proportional to friction velocity, and that the mature crop presents a rougher surface. The relationship between surface drag, τ_0, and roughness length, z_o, is given in figure 12. It is understandable that drag increases as roughness increases, since drag increases with friction velocity.

Inspection of the data in tables 20 and 21 reveals that the zero-plane displacement, d, decreases with friction velocity and that the mature corn has a greater zero-plane displacement than the immature corn.

Row orientation studies were made on August 25, when the wind blew from the northwest perpendicular to the corn rows, and on September 2, when the wind blew from the southeast parallel to the corn rows (table 19).

Figures 13 and 14 and table 22 present the relationships sought in this study. Again, it was found that roughness increased with friction velocity and that cross-row oriented corn was rougher than parallel-row oriented corn, as one would expect. Again, surface drag also in-

[4] Stoller, J. H. Micrometeorological field studies in corn. M. S. Thesis on file, Cornell University, Ithaca, N.Y. 1960.

creased with roughness as expected. Zero-plane displacement decreased with increasing friction velocity and turned out to be consistently less in the cross-row orientation.

The data that have been presented may be inconsistent with what one might expect a priori. It is important, therefore, to examine the results, and to seek a reasonable basis for their explanation. In considering what physical phenomena occur in mature corn, it may be remembered that z_0 is a function of plant height, as well as a function of other surface characteristics; i.e., leaf orientation, plant spacing, and elastic properties of leaf and stalk. It was found that the zero-plane displacement is lowered with increasing friction velocity. This would imply that the wind profile extends further down into the crop canopy and thereby encounters a greater amount of leaf surface to act as a momentum sink. The data demonstrate that this is the case and that, as a consequence, z_0 increases.

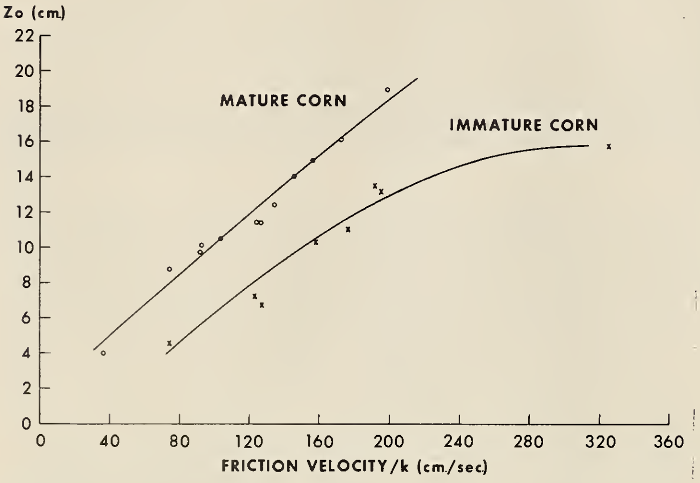

FIGURE 11.—Roughness length (z_0) as a function of windspeed for corn of differing maturity.

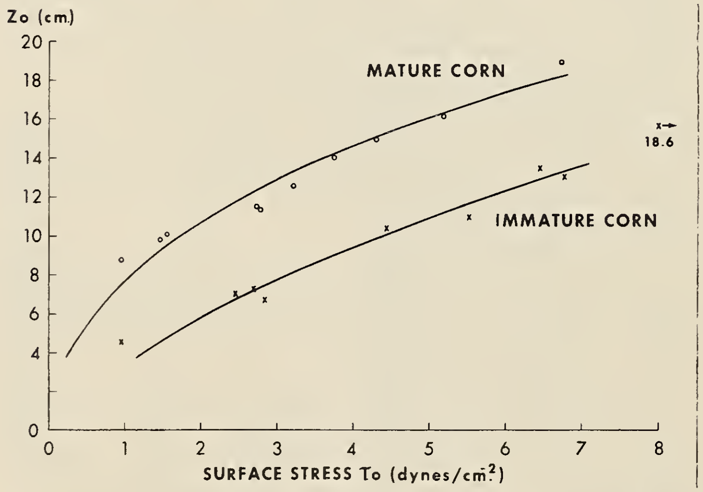

FIGURE 12.—Roughness length (z_0) as a function of shearing stress for corn of differing maturity.

TABLE 19.—*Wind and temperature data for corn maturity studies, Ithaca, N.Y., 1959*

Crop or wind direction and date	Time	Height	Wind velocity	Temperature [1]
Immature corn (180 cm.):	*E.s.t.*	*Cm.*	*Cm./sec.*	*° C.*
July 18	1350	340	450	0.02
		260	400	
		220	360	
		200	340	
		190	325	
	1405	340	495	.10
		260	430	
		220	385	
		200	355	
		190	340	
	1500	340	430	.08
		260	380	
		220	345	
		200	320	
		190	310	
	1515	340	890	.10
		260	750	
		220	660	
		200	605	
		190	570	
	1524	340	545	.02
		260	470	
		220	420	
		200	390	
		190	370	
	1613	340	580	.02
		260	480	
		220	420	
		200	400	
		190	390	
	1625	340	550	.05
		260	470	
		220	425	
		200	380	
		190	360	
	1655	340	435	.05
		260	385	
		220	350	
		200	325	
		190	315	
	1725	340	300	.05
		260	270	
		220	250	
		200	235	
		190	225	
Mature corn (230 cm.):				
July 26	1628	415	185	.10
		335	170	
		295	160	
		275	--------	
		265	150	

See footnote at end of table.

Table 19.—*Wind and temperature data for corn maturity studies, Ithaca, N.Y., 1959*—Con.

Crop or wind direction and date	Time	Height	Wind velocity	Temperature [1]
Mature corn (230 cm.)—Con.	*E.s.t.*	*Cm.*	*Cm./sec.*	*° C.*
July 27	1356	415	--------	0. 10
		335	425	
		295	395	
		275	370	
		265	360	
Aug. 1	1104	420	--------	. 10
		340	500	
		300	460	
		280	445	
		270	435	
	1130	428	--------	. 10
		348	460	
		308	420	
		288	400	
		278	395	
	1200	428	350	. 08
		348	315	
		308	295	
		288	285	
		278	275	
Aug. 2	0901	420	440	. 02
		340	395	
		300	365	
		280	345	
		270	335	
	1208	415	400	. 20
		335	360	
		295	330	
		275	315	
		265	--------	
	1302	415	305	. 25
		335	275	
		295	260	
		275	245	
		265	240	
	1400	415	255	. 20
		335	230	
		295	215	
		275	205	
		265	200	
	1516	420	375	. 20
		340	--------	
		300	320	
		280	305	
		270	295	
	1602	415	310	. 09
		335	280	
		295	260	
		275	250	
		265	240	
	1700	420	375	. 20
		340	--------	
		300	320	
		280	305	
		270	295	

See footnote at end of table.

Table 19.—*Wind and temperature data for corn maturity studies, Ithaca, N.Y., 1959*—Con.

Crop or wind direction and date	Time	Height	Wind velocity	Temperature [1]
Wind cross rows (250 cm.):	*E.s.t.*	*Cm.*	*Cm./sec.*	*° C.*
Aug. 25	1108	770	410	0. 10
		720	--------	
		670	390	
		620	380	
		570	370	
		520	355	
		470	340	
		445	330	
		395	310	
		345	290	
		295	250	
	1120	770	550	. 10
		720	--------	
		670	520	
		620	510	
		570	500	
		520	480	
		470	460	
		445	450	
		395	420	
		345	390	
		295	350	
	1142	770	470	. 10
		720	460	
		670	450	
		620	430	
		570	420	
		520	400	
		470	380	
		445	370	
		395	360	
		345	330	
		295	290	
	1153	770	670	. 10
		720	650	
		670	640	
		620	--------	
		570	610	
		520	570	
		470	--------	
		445	540	
		395	510	
		345	470	
Wind down rows (250 cm.):		295	420	
Sept. 2	0908	770	390	. 10
		720	--------	
		670	380	
		620	360	
		570	350	
		520	340	
		470	320	
		445	--------	
		395	300	
		345	280	
		295	245	
	0915	770	360	. 09
		720	350	
		670	--------	
		620	340	

See footnote at end of table.

TABLE 19.—*Wind and temperature data for corn maturity studies, Ithaca, N.Y., 1959*—Con.

Crop or wind direction and date	Time	Height	Wind velocity	Temperature[1]
Wind down rows (250 cm.)—Con.	*E.s.t.*	*Cm.*	*Cm./sec.*	*° C.*
Sept. 2—(Con.)	0915	570	330	0.09
		520	320	
		470	300	
		445	290	
		395	280	
		345	260	
		295	225	
	0920	770	600	.08
		720	580	
		670	570	
		620	--------	
		570	530	
		520	510	
		470	--------	
		445	480	
		395	--------	
		345	410	
		295	360	
	0935	770	460	.10
		720	450	
		670	440	
		620	--------	
		570	420	
		520	--------	
		470	380	
		445	370	
		395	350	
		345	--------	
		295	280	

[1] Temperature difference between top and bottom thermocouple units.

TABLE 20.—*Wind profile data in relation to immature corn, Ithaca, N.Y., 1959*

Profile No.	u^*/k	z_0	d	Corn height
	Cm./sec.	*Cm.*	*Cm.*	*Cm.*
1	75.3	4.5	104	180
2	123.0	7.1	93	180
3	123.5	7.3	93	180
4	127.0	6.9	93	180
5	158.6	10.6	90	180
6	177.3	11.1	84	180
7	191.9	13.6	82	180
8	196.2	13.1	84	180
9	326.6	15.8	84	180

TABLE 21.—*Wind profile data in relation to mature corn, Ithaca, N.Y., 1959*

Profile No.	u^*/k	z_0	d	Corn height
	Cm./sec.	*Cm.*	*Cm.*	*Cm.*
1	36.1	4.0	154	230
2	73.4	8.7	122	230
3	90.8	9.7	120	230
4	92.9	10.1	120	230
5	104.9	10.5	119	230
6	124.7	11.6	118	230
7	126.0	11.5	111	230
8	134.9	12.5	112	230
9	145.9	14.1	106	230
10	156.4	15.0	105	230
11	171.5	16.2	94	230
12	195.6	19.0	80	230

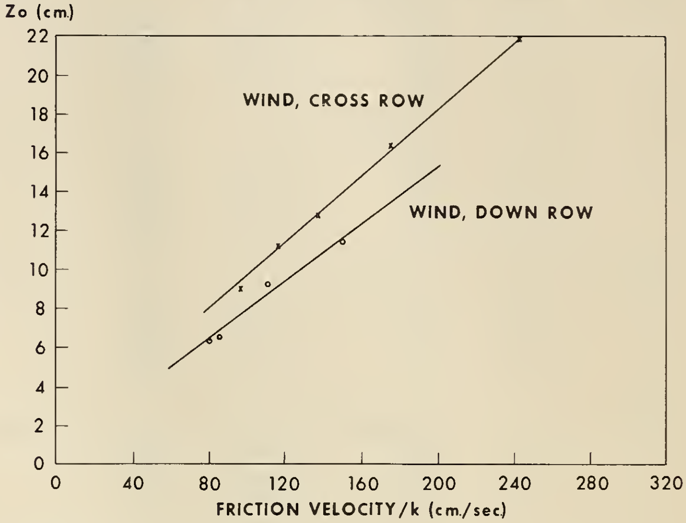

FIGURE 13.—Roughness length (z_0) as a function of windspeed, depending upon corn row orientation.

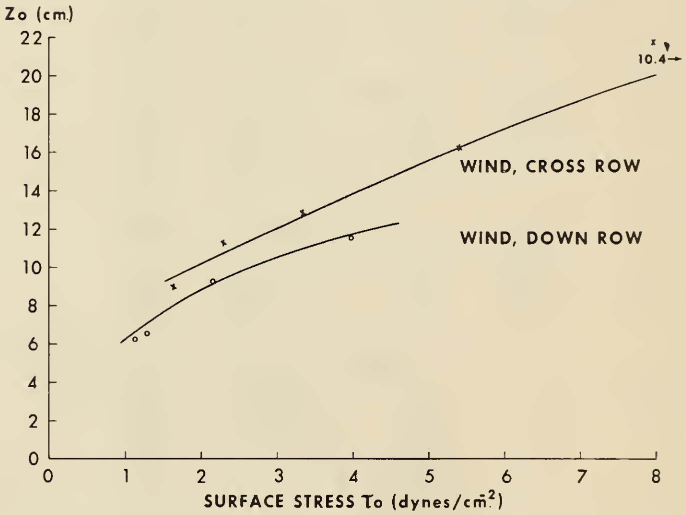

FIGURE 14.—Roughness length (z_0) as a function of shearing strength, depending upon corn row orientation.

TABLE 22.—*Wind profile data of oriented corn rows, Ithaca, N.Y., 1959*

Wind direction and profile No.	u^*/k	z_0	d	Corn height
Wind down row:	*Cm./sec.*	*Cm.*	*Cm.*	*Cm.*
1	80. 0	6. 3	180	250
2	85. 5	6. 5	180	250
3	110. 9	9. 2	180	250
4	150. 4	11. 5	170	250
Wind cross row:				
1	96. 8	9. 0	160	250
2	116. 7	11. 2	160	250
3	137. 8	12. 7	140	250
4	175. 0	16. 2	140	250
5	243. 0	21. 9	130	250

One interesting point should be brought up here concerning the roughness value at the highest friction velocity in the immature corn (see fig. 11). Under high friction velocities, the immature elastic stalks without tassels apparently bend over, causing less change in the zero-plane displacement and, consequently, roughness than in the more rigid mature stalks with tassels.

Rider's (*20*) investigations of friction velocity over oats; Deacon's (*2*) investigations over tall grass; and Tani's and Inoue's (*23*) investigations over growing ricefields all demonstrate the opposite relationships to those found in this study. They found that with increasing wind velocity the zero-plane displacement increased. Evidently, at light to moderate windspeeds the individual elements in their plant surfaces acted as a "rough" surface to remove more momentum from the fluid than when the velocities became great enough to bend the flexible stalks and orient the leaves so that the surface became less "rough."

In subsequent investigations over mature ricefields, Tani and Inoue (*24*) found that the more rigid stalks did not bend and "smooth out," and as a result the zero-plane displacement and roughness changed in the same fashion as in the corn crop of the present study. Similar results have been found in mature wheat by Penman and Long (*19*).

Further studies by Tani, Inoue, Isobe, and Horibe (*25*) with mature and immature rice have indicated increasing and decreasing relationships with both z_0 and d with windspeed, depending upon range of winds.

The results in the row orientation study may be explained along similar lines. Evidently, where the wind blows parallel to the rows, the fluid takes the path of least resistance between the rows. In doing this, the stalks remove less momentum from the wind and create less turbulent activity than in those rows perpendicular to the wind.

Since the zero-plane displacement is a statistical reference plane where turbulent activity appears to commence, it would be lowered toward the ground as turbulence in the top of the crop increases. Thus, for a given friction velocity, the roughness (and potential turbulence) becomes greater with decreasing zero-plane displacement. This phenomenon is evidently more pronounced in the cross-row orientation than in the parallel-row orientation. With the increase in momentum transfer due to cross-row orientation, one can conclude that mass transfer potential is also increased with cross-row orientation.

PHOTOSYNTHESIS

By Conrad S. Yocum

BACKGROUND

Although the contribution of photosynthesis to the heat budget of the earth may be a relatively minor one ($\leqq 15$ percent), the process is an important one in that it provides all the food, oxygen, and, until recently, nearly all our energy resources. Qualitatively, the overall process may be illustrated by the following equation:

$$CO_2 + H_2O + \text{light} \xrightarrow[\text{plants}]{\text{green}} [CH_2O] + O_2 + \text{energy stored}$$

where $[CH_2O]$ represents a number of carbon compounds at the reduction level of carbohydrate or of carbon itself (e.g., starch, cellulose). From quantitative experiments in the laboratory the following stoichiometrical relations have been established:

$$1 \text{ mole } CO_2 + 1 \text{ mole } H_2O + 7-12 \text{ mole quanta} \underset{\text{(Einstein's)}}{\longrightarrow}$$

$$1 \text{ mole } [CH_2O] + 1 \text{ mole } O_2,\ \Delta F = 110-120 \text{ Kcal.}$$

where ΔF is the change in free energy.

To compute the thermal efficiency of photosynthesis the energy content of the absorbed light is required. For the average wavelength of photosynthetically active light (0.4μ to $0.7\mu = 0.55\mu = 5.5\times 10^{-5}$ cm.) the conversion factor is:

$$6.6\times 10^{-27} \text{ erg sec.} \times \frac{3\times 10^{10} \text{ cm./sec.}}{5.5\times 10^{-5} \text{ cm.}}$$

$$\times 2.39\times 10^{-8} \frac{\text{cal.}}{\text{erg}} \times 6.02\times 10^{23} = 52 \text{ Kcal./Einstein}$$

where one Einstein, or one mole quantum equals 6.02×10^{23} (Avogadro's number) quanta.

If the highest measured efficiencies are 7 Einsteins per mole of oxygen produced, or carbon dioxide assimilated, the maximum thermal efficiency becomes:

$$\frac{\text{stored}}{\text{absorbed}} = \frac{120 \text{ Kcal.}}{7\times 52 \text{ Kcal.}} = 0.33 = 33 \text{ percent.}$$

If we know the wavelength distribution of natural light (sun, sky, and clouds), the fraction of this light absorbed by the vegetation, and the dry matter production or rate of photosynthesis under natural conditions, we can estimate the efficiency of light energy conversion for these natural conditions. Although the wavelength distribution of the solar radiation is not constant with time, we estimate that 33 to 46 percent lies between 0.4μ and 0.7μ. Similar values are estimated for sky and cloud radiation.

The absorption of light by plant populations can be measured directly (work in progress for the 1960 growing season) or calculated from reflection data. Monteith (*15*) estimated the reflection by cultivated plants to be 10 percent between wavelengths 0.4μ and 0.7μ. Thus, up to 90 percent may be absorbed by the plants, depending on the age and density of the plants. The maximum thermal efficiency expected for plants in nature becomes the product of the maximum efficiency, the fraction of light absorption and the fraction of the natural light between 0.4μ and 0.7μ.

$$0.33\times 0.9\times 0.46 \cong 0.14, \text{ or } 14 \text{ percent.}$$

A number of factors may lead to lower measured efficiencies. Among them are incomplete absorption of light, carbon dioxide releasing processes such as respiration that proceeds 24 hours per day, lack of water or essential mineral elements, and low rate of supply of carbon dioxide.

PHOTOSYNTHESIS UNDER FIELD CONDITIONS

The rate of photosynthesis during short intervals can be measured by the gas exchange of plants in a closed system[5] or by the aerodynamic carbon dioxide exchange via turbulent transfer (*10, 12, 16*). The latter method was used to obtain the data presented below. Under equilibrium conditions (i.e., wind profiles fully developed), the carbon dioxide content of the air, C, and the wind velocity, $\bar{u}$, were recorded at several heights, z, above the soil in a field of growing

[5] Moss, D. N. Photosynthesis under field conditions. Ph. D. Thesis. On file at Cornell University, Ithaca, N.Y. 1959.

corn. Also measured were the zero plane displacement, d, and the roughness length, z_o. The vertical flux density of carbon dioxide per cm.^{2}, P, was then estimated from the following equation (*7*):

$$P=-\frac{1}{3}\frac{K}{\gamma}\left[\bar{u}_{2(z+D)}-\bar{u}_{(z+D)}\right]\left[C_{2(z+D)}-C_{(z+D)}\right] \quad (15)$$

where K=diffusion coefficient of carbon dioxide in the air; γ=kinematic viscosity of the air; $K/\gamma \cong 1$; D=effective displacement, and is equal to $d+z_0$. Some representative data are presented in table 23.

TABLE 23.—*Data obtained for P (equation 16) in a field of corn, Aug. 25, 1959* [1]

z	$\bar{u}$	C	$z+D$
Cm.	*Cm./sec.*	*G./cm.^{3}*	*Cm.*
716	620	614×10^{-9}	596
567	600	602	437
442	540	600	312
342	450	598	122

[1] Wind velocity, $\bar{u}$; carbon dioxide concentration, C, at various heights above the ground, z. The effective displacement, D, was 130 cm., and the incident radiation flux was 1.2 cal./cm.^{2}/min.

The rates so obtained were quite variable, but an average value of approximately 0.3×10^{-6} grams CO_2/cm.^{2}/sec. will be used for subsequent calculations in this report. The thermal efficiency was estimated from

$$\frac{120{,}000 \text{ calories}}{44 \text{ grams } CO_2}=2.7 \text{ Kcal./gram } CO_2$$

and an incident radiation flux of 1.2 cal./cm.^{2}/min.:

$$\frac{\dfrac{0.3\times10^{-6}\text{ grams } CO_2}{\text{cm.}^2\times\text{sec.}}\times\dfrac{60\text{ sec.}}{\text{min.}}\times\dfrac{2.7\text{ Kcal.}}{\text{grams } CO_2}}{\dfrac{1.2\text{ cal.}}{\text{cm.}^2/\text{min.}}}=4.0 \text{ percent.}$$

If the estimate of the maximum efficiency (10 to 14 percent) is correct, 4/14, or 29 percent, of the photosynthetic potential was realized under conditions of our observations.

The photosynthetic rate of this plant population may now be compared to that of an individual leaf. A single cornleaf from the same population, and normal to the rays of the sun, consumed up to 1.7×10^{-7} grams CO_2/sec. cm.^{2} [6] That is, the rate for the population of leaves was approximately twice that of a single, fully exposed leaf. Measurements of the leaf area in this same population show 4 to 5 cm.^{2} per cm.^{2} of the earth's surface. That is, the leaf area index, *LAI*, is 4 to 5.

If all of the leaves were fully exposed to the sun, the relative rate for the population is approximately the product of the *LAI*, the cosine of the sun's angle to horizontal and a factor $2/\pi$ that partly accounts for the semicylindrical form which each leaf approaches:

$$4 \text{ to } 5\times0.8\times\frac{2}{3.14}\simeq2$$

CARBON DIOXIDE TRANSFER SYSTEMS

From the above-mentioned vertical CO_2 flux down into a photosynthesizing population of plants, P, and the CO_2 gradient, $\frac{dC}{dl}$, the CO_2 transfer coefficient, Ke, may be estimated as follows:

$$P=-Ke\frac{dC}{dl}. \quad (16)$$

Rearranging, and substituting data of August 25, 1959, gives us:

$$Ke=\frac{2\times10^{-7}\text{ gram/cm.}^2\text{ sec.}\cdot225\text{ cm.}}{4\times10^{-9}\text{ gram/cm.}^3}$$

$$=1\times10^4 \text{ cm.}^2\text{/sec.}$$

A similar value is obtained from the data at heights z=716 and 442 cm. in table 23. It should be pointed out that Ke is not a constant, but depends upon z, u, z_0, and d. Estimation of Ke closer to the plants is in progress.

Ke may be compared to the molecular diffusion coefficient (generally referred to as D in the literature, but not to be confused with D, the effective displacement used here), 0.14 cm.^{2}/sec. The molecular diffusion coefficient in water is 1.8×10^{-5} cm.^{2}/sec., and in plant tissue it is 8×10^{-6} cm.^{2}/sec. (*1*).

From the rate of carbon dioxide withdrawal via photosynthesis and the carbon dioxide gradients, it is possible to estimate an upper limit for the thickness of the aqueous and gaseous systems through which carbon dioxide is transferred in laminar flow and molecular diffusion. No measurements of carbon dioxide gradients adjacent to, and within, leaves are yet available, but approximations are used in the following estimates.

First, consider the maximum distance through which carbon dioxide may penetrate via molecular diffusion in laminar flow of air across the leaf:

$$P=-D\frac{dC}{dl}. \quad (17)$$

[6] Hesketh, J. Photosynthesis: Leaf chamber studies with corn. Ph. D. Thesis. On file at Cornell University, Ithaca, N.Y. 1961.

The carbon dioxide gradient, dC, across the laminar layer is estimated to be 10 percent of the carbon dioxide content of the air. Rearranging and using the observed rate for a single leaf give:

$$l=\frac{0.14 \text{ cm.}^2/\text{sec.}\times 5.4\times 10^{-8} \text{ g./ml.}}{1.7\times 10^{-7} \text{ g./cm.}^2/\text{sec.}}=0.05 \text{ cm.}$$

If the thickness of the laminar layer is close to this estimate, the turbulent boundary layer may extend into the region of the hairs, which protrude about 1 millimeter from the surface of corn leaves. Thus, hairs may serve to increase the aerodynamic roughness, and thereby increase the rate of carbon dioxide exchange during photosynthesis. Wind tunnel experiments are planned to test this hypothesis.

Second, consider the maximum thickness of a leaf, assuming the leaf to be a completely liquid system, and the concentration of carbon dioxide to be zero in the chloroplasts. The concentration of the carbon dioxide at the leaf surface is now estimated to be about 80 percent of that at several meters above the plants, or 2.4×10^{-4} atm. The concentration of carbon dioxide dissolved in the plant tissue $[CO_2]$ is given by:

$$[CO_2]=pCO_2\cdot \propto CO_2 \frac{1 \text{ mole}}{22.4 \quad 1 \text{ atm.}}$$

where pCO_2 is the partial pressure (atm.) of the carbon dioxide, and $\propto CO_2$ is the solubility coefficient of CO_2(ml./m.).

$$[CO_2]=\frac{2.4\times 10^{-4}\times 0.75}{22.4}=1\times 10^{-5} \text{ M}$$

$$=1\times 10^{-8} \text{ M/cm.}^3=4\times 10^{-7} \text{ g./cm.}^3$$

Again solving for l, and assuming carbon dioxide diffusing through upper and lower surfaces at equal rates:

$$l \text{ liq.}=\frac{8\times 10^{-6} \text{ cm.}^2/\text{sec.}\cdot 4\times 10^{-7} \text{ g./cm.}^3}{1.7\times 10^{-7} \text{ g./cm.}^2/\text{sec.}}$$

$$=4\times 10^{-5} \text{ cm.}$$

Thus, the maximum thickness of an hypothetical "all liquid phase" leaf would be twice the diffusion path, or approximately 1 micron, μ. However, a cornleaf is more nearly 300μ thick. But at least one-half the leaf volume is gas space with a diffusion coefficient $\sim 10^5$ times that of the liquid phases of the cells. Examination of cornleaf sections in three planes reveals many of the cells to approximate cylinders of 8μ radius. The chloroplasts are slightly flattened spheres with diameters $\sim 3\mu$. The maximum diffusion path from the surface of the cell to the chloroplasts was estimated as 4μ. For a respiring cylinder (*4*):

$$C_i=C_R-\frac{q}{4D}(R^2-r_i^2) \qquad (18)$$

where C_i is the concentration at r_i, the radius of the inner nonmetabolic cylinder; C_R is the concentration at the surface of the cylinder of radius, R; and q is the rate of uptake per unit volume per unit time. Let $C_i=0$, and

$$q=\frac{4DC_R}{(R^2-r_i^2)}. \qquad (19)$$

If D is used for tissue as above; let R and r_i $=8\mu$ and 4μ, respectively, and assume all the cells to be cylinders of indefinite length; and assume the partial pressure of carbon dioxide to be 16 percent less at the cell surfaces than at the leaf surface (*28*):

$$q=\frac{4\times 8\times 10^{-6}\frac{\text{cm.}^2}{\text{sec.}}\times\left(\frac{1-0.16}{1}\right)\times 4\times 10^{-7}\frac{\text{g.}}{\text{cm.}^3}}{(8\times 10^{-4} \text{ cm.})^2-(4\times 10^{-4} \text{ cm.})^2}$$

$$=2\times 10^{-5}\text{g./cm.}^3/\text{sec.}$$

If each square centimeter of cornleaf weighs 0.016 gram (data of J. H. Shinn) and if the tissue density is 1 gram/cm.^{3}, the rate of carbon dioxide diffusion into the cells of 1 cm.^{2} of leaf surface is

$$\frac{2\times 10^{-5}\text{g.}}{\text{sec.}\cdot\text{cm.}^3}\times\frac{0.016 \text{ cm.}^3}{1.00 \text{ cm.}^2}=3\times 10^{-7}\text{g. } CO_2/\text{cm.}^2/\text{sec.}$$

DISCUSSION

To date, most detailed studies of photosynthesis have been made in the laboratory under controlled conditions. Of those studies made under natural conditions, many have relied on the dry matter production as a measure of the rate. It is now possible to make rate measurements over relatively short periods by measuring the aerodynamic transfer rate of carbon dioxide from the atmosphere to plants. In this method, it is assumed that the turbulent gas exchange is analogous to the momentum exchange via turbulent processes. Confidence in the method, therefore, depends upon agreement of the results with those obtained by independent procedures. The few data reported here for the aerodynamic transfer (2 to 4×10^{-7} g. CO_2/cm.^{2}/sec.) are consistent with those obtained by the single-leaf chamber technique. The aerodynamic results are also reasonably consistent with dry matter production. The data of table 23, when used to calculate the yield, give $\sim$ 20 tons dry matter per acre. The measured yield for this plant population was 13 tons.[7]

[7] Musgrave, R. B. Unpublished data.

Although sunlight may be the least expensive reactant to photosynthesis, it is important to know what fraction of the potential light energy conversion is realized under natural conditions. This fraction was about 0.29 in the case reported here—a cornfield in late August at 42° latitude. In the rest of the report, an attempt has been made to evaluate some components of the carbon dioxide transfer systems. Comparisons of these to the potential characteristics may lead to suggestions for increasing the efficiency of photosynthesis under natural conditions.

The approach was similar to that of Van den Honert (*27*) for the transfer of water from the soil through the plant to the atmosphere, and of Gaastra (*5*) for the carbon dioxide and water vapor exchange by plants. Applying Ohm's law [in Gradmann (*6*)], Van den Honert and Gaastra showed that each step in a series of transfers had a resistance, R, and a potential drop, E, and then applied the laws of series resistors. Now R of Ohm's law equals l/DA of Fick's diffusion law, where D is the diffusion or transfer coefficient; A and l are the area and distance of the diffusion or path, respectively. Where possible in this report, the rates of transfer, the coefficients, and the dimensions of the systems have been related. For example, the transfer coefficient for the turbulent atmosphere several meters above the plants, Ke, was $\sim 10^4$ times that of the molecular diffusion coefficient from the laminar layer ~ 0.05 cm. thick. For the intercellular air spaces Ke was $\sim 10^9$ times that of molecular diffusion through the liquid phases, $\sim 4\mu$ thick, of plant cells. The measured rates of photosynthesis are, therefore, only possible with relatively very short liquid diffusion paths across large areas.

The diffusion resistance of a gas-liquid interface has frequently been assumed to be relatively high. This generalization may result from the generally low permeability of cell membranes to ions such as $K+$, $Na+$, and NO_3^-. An estimate of the carbon dioxide diffusion coefficient, D, through a water-air interface can be made from Roughton's data (*21*), by assuming a 20 cm.^{2} area and 10^{-3} cm. thickness of the stationary film. For these conditions, $D = 2.2 \times 10^{-5}$ cm.^{2}/sec., a value that nearly equals 1.8×10^{-5} cm.^{2}/sec., D, for carbon dioxide diffusing through water alone.

Control of the rate of gas exchange by the plant lies in the stomata, small pores of the leaf surface that open and close. It has recently been shown that not only light but also carbon dioxide concentration can control the stomatal apertures (*5*, and others).[8] High carbon dioxide partial pressures even in the light decrease the aperture, without appreciably decreasing the rate of carbon dioxide uptake (*3*). This has led to a lower rate of water vapor loss via transpiration. Thus, a more efficient aerodynamic carbon dioxide transfer may lead to a more favorable photosynthesis/transpiration ratio, an important factor for the evolution of plants, and for agricultural practice in arid and semiarid regions.

[8] See also footnote 5.

CONCLUSIONS

Conclusions based on experimental data gathered during the first year of this effort were as follows:

1. As one might expect, the seasonal trends in the heat balance components reflect the influence of the vegetative leaf cover.

2. The difference in surface cover characteristics drastically influence the partition of thermal energy at the surface.

3. To obtain a complete evaluation of the energy balance at the vegetative surface, the photosynthesis term must be measured.

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Annual Report

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